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AMMONIA STRIPPING MATHEMATICAL MODEL FOR WASTE WATER TREATMENT

IIT Research Institute, Chicago, Illinois

PREPARED FOR
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AMMONIA STRIPPING MATHEMATICAL MODEL FOR WASTE WATER TREATMENT

June 4, 1968 through December 4, 1968

IITRI Project C6152

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FOREWORD

This is Report No. IITRI-C6152-6 (Final Report) of IITRI Project C6152, entitled "Ammonia Stripping Mathematical Model for Waste Water Treatment." The report covers the period from June 4 through December 4, 1968.

Permission has been requested from the appropriate sources to reproduce, in this report, a number of the tables and figures.

Respectfully submitted,

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ABSTRACT

Two computer programs were developed for the design of ammonia stripping towers: (1) a design program for countercurrent towers and (2) a design for cross-flow towers. The programs determine the dimensions of the tower required for given operating conditions, evaluate investment and operating costs of the process, and provide information on pH requirements, and the exit temperature on the wastewater so that freezing conditions can be predicted.

Particle, splash, and film packings can be evaluated for countercurrent towers, and splash packing for cross-flow towers.

In the case of countercurrent towers, the program finds the liquid and gas flow rates which yield a minimum total annual cost.

The design equations are in general form, with parameters read in by the program, so that experimental data can readily be used as it is accumulated.

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COUNTERCURRENT TOWER

I. INTRODUCTION

In the normal biological degradation of nitrogen-containing waste the material is converted to ammonia in solution and may eventually be converted to nitrate in solution. This nitrate serves as a nutrient for algal growth in the stream which receives the effluent. Studies[34] at the South Tahoe Public Utility District indicated that there is a point in the biological treatment process where the nitrogen can be removed as ammonia. This point is after a tertiary lime treatment stage.

A. The Physical Process of Ammonia Stripping

Ammonium ions exist in equilibrium with molecular ammonia and hydrogen ions in the wastewater according to the reaction.

$$NH_3 + H_2O \rightleftharpoons NH_4^+ + OH^- \qquad \text{(R1)}$$

As the pH of the wastewater is increased, the equilibrium is displaced to the left, and HN_3 is liberated as a gas. Even when the ammonia is in the NH_3 form, its vapor pressure is low, and it is necessary to agitate the solution with a large volume of inert gas such as air to remove the ammonia gas from the wastewater. This process is called stripping.

The gas used for stripping can be water vapor. Water vapor can be generated by applying vacuum to the wastewater itself. However, calculations presented in the computer program description show that the weight of air needed for stripping is about 4 times the weight of wastewater to be treated. Vacuum stripping is not feasible because it would be necessary to vaporize practically all of the wastewater.

On the other hand a process of stripping with air has already been shown to be feasible on a pilot plant scale. This can be accomplished by continuous countercurrent contact of liquid and gas in a packed tower, which is a vertical column filled with packing or devices of large surface. The liquid is distributed over the packing and trickles down through the packed bed, thus exposing a large surface to contact the gas.

The air stream passing through the tower has an ammonia concentration less than that which would be in equilibrium with the wastewater, and this difference in concentration provides the driving force for desorption of ammonia.

B. What the Computer Program Does

To solve a new design problem such as this one, a method of obtaining the minimum cost typically used in industrial practice is as follows: (1) determine the height of tower required for a given packing; (2) determine the pressure drop; (3) for several different sets of values of the gas and liquid loading rates make a series of plots of the total cost vs. the gas rate for different liquid rates; (4) choose the combination of gas and liquid rates which gives the minimum total cost.

A less tedious and more sophisticated design method may be used as was done for this project. The total annual cost is the summation of the individual installed cost amortized over a reasonable period of time of such items as the tower, packing, fan, pump, basin, etc., and the fan and water pumping power cost. It is possible to express each of these costs in terms of unknown design variables such as the height and cross-sectional area of the tower, gas rate, liquid rate etc. When these expressions are combined to give the total annual cost it becomes a function only of the gas and liquid rates The most economic design can be determined by differentiating the total cost equation with

respect to the gas and liquid rates, setting the resulting two equations equal to zero and solving for the gas and liquid rates that give a minimum annual cost. This procedure was accomplished by numerical methods on the computer. The design data that the program yields is:

(1) The minimum total annual cost and how it is distributed among the various items

(2) Optimum gas and liquid rates

(3) Height and cross-sectional area of tower that gives these gas and liquid rates

(4) Pressure drop

(5) pH necessary for operation, and change in pH

(6) Exit temperature change of liquid due to contact with air

The mathematical basis for the computer program is presented in the remainder of this report. The program can be used without studying this information, by referring directly to Section IX which describes the input and output of the computer program.

II. EQUILIBRIUM BETWEEN NH_3 and NH_4^+ IN ALKALINE SOLUTIONS

The reaction that occurs when gaseous ammonia is contacted with an aqueous phase is

$$NH_3 + H_2O \rightleftharpoons NH_4^+ + OH^- \qquad (R1)$$

The equilibrium relationship for the distribution of the above species is

$$K_b = \frac{[NH_4^+][OH^-]}{[NH_3]} \qquad (1)$$

where K_b is the equilibrium constant.

Since the net charge in solution must be zero according to the electroneutrality principle, one may write

$$[OH^-] = [H^+] + [NH_4^+] \pm [\text{any other positive or negative charged ions}] \qquad (2)$$

The only other important buffering ions are carbonate and phosphate. The effect of carbonate is considered in Section IV. It is assumed that ammonia stripping is preceded by a lime treatment that removes most of the phospate.

A mass balance on nitrogen results in the equation

$$C_N = [NH_3] + [NH_4^+] \tag{3}$$

where C_N is total concentration of ammonia including the molecular and ionic species. Another equilibrium relationship may be written since the product of the concentrations of hydrogen ions and hydroxide ions must satisfy the relation

$$K_w = [H^+][OH^-] \tag{4}$$

where K_w is the ion product for water.
If the fraction of ammonia in molecular form is defined as

$$\%NH_3 = \frac{[NH_3]}{C_N} \tag{5}$$

equations 1, 2, 3, 4, and 5 may be solved simultaneously to yield

$$[H^+] = \frac{(1 - \%NH_3)}{\%NH_3} \left(\frac{K_w}{K_b} \right) \tag{6}$$

Equation 6 may be used to calculate a pH sufficient for a given set of operating conditions. If the concentration of ammonia in the entering stream is denoted as TOTNH3 and that of the effluent as NH3OUT, the fraction of ammonia to be removed from the entering stream is

$$\frac{\text{TOTNH3} - \text{NH3OUT}}{\text{TOTNH3}}$$

It is sufficient that the pH of the influent be high enough that this fraction of ammonia is in molecular form. (Actually it could be less than this because removal of NH_3 will drive Reaction R1 to the left, but this effect is relatively unimportant and is neglected.) Thus, for a sufficient fraction of ammonia to be in molecular form, it is sufficient that the pH in the entering stream be

$$pH = -\log\left[\left(\frac{K_w}{K_b}\right)\ \frac{NH3OUT}{TOTNH3 - NH3OUT}\right] \qquad (7)$$

For 25°C, $K_b = 1.8 \times 10^{-5}$, $K_w = 1 \times 10^{-14}$, TOTNH3 = 40 mg/l, and NH3OUT = 1 mg/l, the pH is 10.85. Under similar conditions at Lake Tahoe, it was found that a pH of 10.8 gave the most successful operation of the tower.

The pH drop across the tower due to the transfer of ammonia from the liquid stream into the gas stream can be estimated as follows. According to Reaction 1, for each mole of NH_3 transferred to the gas, one mole of OH^- will be lost by combining with NH_4^+ to form NH_3 and H_2O. Thus, the change in the amount of NH_3 will equal the maximum change in the amount of NH_4^+ which in turn will equal the maximum change in the amount of OH^-. Therefore, the maximum OH^- concentration drop across the tower due to the transfer of NH_3 from liquid to gas is

$$\frac{(TOTNH3 - NH3OUT)(1 - FRACTF)}{17 \times 10^3\ (mg/mole\ of\ NH_3)}$$

where (TOTNH3 and NH3OUT) are expressed in mg/l and

FRACTF is (TOTNH3 - NH3OUT)/TOTNH3

For TOTNH3 = 40 mg/l, NH3OUT = 1 mg/l, and an entering pH of 11 or 1×10^{-3} mole of OH^-/l, the OH^- concentration drop is

5.9×10^{-5} mole/l, so no significant reduction in pH across the height of the tower occurs. The experimental results at Lake Tahoe are in agreement with this conclusion.

III. TEMPERATURE EFFECT DUE TO AIR-WATER CONTACT

It is shown in Appendix that the temperature drop occurs mainly at the top of the tower and that the mean liquid temperature is very close to the wet bulb temperature of the entering air. Thus, the analysis of the ammonia stripping tower can be based upon isothermal design principles using the entering wet bulb temperature of the air as the design temperature for a first approximation. Then, the temperature profile and mean temperature can be calculated, and the first approximation checked. If the wet bulb temperature and mean temperature differ significantly, the design procedure is repeated using the mean temperature.

IV. ABSORPTION OF CO_2

The rate of absorption of CO_2 into water at pH 7 has been found to be negligibly show. However, the rate into strongly alkaline solutions is fast. The amount of CO_2 present in the air used to strip ammonia from wastewater is potentially capable of neutralizing all of the lime alkalinity before the ammonia is removed. The question is whether the rate of CO_2 absorption is appreciable at the typical operating pH of an ammonia stripping tower. It is shown in the Appendix that the drop in pH across the tower due to CO_2 absorption is negligible.

V. FLOODING

To check whether the flow rates are such that the column does not flood for particle packing one may use an equation of Sawistowski[31]

$$\left[\ln \frac{\left(G_F^2\right)a}{g\varepsilon^3 \rho_L \rho_G}\right] \left(\frac{\mu_L}{\mu_W}\right)^{0.2} = -4\left(\frac{L}{G}\right)^{1/4} \left(\frac{\rho_G}{\rho_L}\right)^{1/8} \qquad (8)$$

The generalized graphical correlation for flooding rates in packed columns is represented by this empirical equation.

The criterion for the column not to flood is $G < G_F$. It turned out that for typical operating conditions that the tower is operating under conditions far removed for flooding to occur.

VI. ESTIMATION OF EFFECT OF TEMPERATURE ON PHYSICAL PROPERTIES[20]

A. Henry's Constant[8,38]

For NH_3-air-H_2O system Henry's constant is m = .88 at 77°F.

The ration of Henry's constant at temperature T (°F) to that at T = 77°F is

$$HENR = 10^{(.01233\ T\ -\ .95)} \tag{9}$$

B. Viscosity of the Liquid[12]

The viscosity of water is μ_L = 2.42 lb/ft hr at 68°F.

The ratio of the viscosity of a liquid at temperature T (°F) to that at T = 68°F is

$$MULR = \frac{78.6}{(T + 10)} \tag{10}$$

C. Viscosity of the Gas[28]

The viscosity of air is μ_G = .0414 lb/ft hr at 32°F.

The ratio of the viscosity of a gas at temperature T (°F) to that at T = 32°F is

$$MUGR = \left(\frac{T + 460}{492}\right)^{1/2} \tag{11}$$

D. Density of the Liquid[28]

The density of water is ρ_L = 62.93 lb/ft^3 at 68°F.

The ratio of the density of a liquid at temperature T (°F) to that at T = 68°F is

$$RHOLR = \left(\frac{212 - T}{144}\right)^{1/3} \tag{12}$$

E. Density of the Gas[28]

The density of air is ρ_G = .0808 lb/ft^3 at 32°F.

The ratio of the density of a gas at temperature T(°F) to that at T = 32°F and 1 atm is

$$\text{FHOGR} = \frac{492}{T + 460} \tag{13}$$

F. Diffusivity of a Gas into a Liquid[28]

The diffusivity is $\mathscr{D}$ = 7.10 x 10^{-5} ft^2/hr for the NH_3 - H_2O system at 68°F.

The ratio of the diffusivity of a gas into a liquid at temperature T(°F) to that at T = 68°F is

$$\text{DLR} = \frac{(T + 460)}{528\ \text{MULR}} \tag{14}$$

G. Diffusivity of a Gas into a Gas[28]

$\mathscr{D}$ = .77 ft^2/hr for NH_3-air system at 32°F.

The ratio of the diffusivity of a gas into a gas at temperature T(°F) to that at T = 32°F is

$$\text{DGR} = \left(\frac{T + 460}{492}\right)^{3/2} \tag{15}$$

H. Schmidt Number

The ratio of the Schmidt number of the liquid-gas system at temperature T(°F) to that at T = 68°F is

$$\text{SCLR} = \frac{\text{MULR}}{(\text{RHOLR})\,(\text{DLR})} \tag{16}$$

The ratio of the Schmidt number for the gas-gas system at temperature T(°F) to that at T = 32°F is

$$\text{SCGR} = \frac{\text{MUGR}}{(\text{RHOGR})\,(\text{DGR})} \tag{17}$$

I. Equilibrium Constants

The equilibrium constant for ammonia and water as a function of temperature is

$$K_b = 1.8 \times 10^{-5} \exp[-6348.5/(.5555\ T + 255.2) + 21.3] \qquad (18)$$

where $K_b = \dfrac{[NH_4^+][OH^-]}{[NH_3]}$

Equation 18 is based upon the Van't Hoff equation[19]

$$\left(\frac{\partial \ln K_b}{\partial t}\right)_{p,\ \text{concentration}} = \left[\frac{\Delta H^\theta}{RT^2}\right] \qquad (19)$$

where R is the universal gas constant and ΔH^θ the heat of ionization. Assuming ΔH^θ is independent of temperature, Equation 19 may be integrated to give

$$K_b = K_b\Big|_{25°C}\left\{\exp\left[-\frac{\Delta H^\theta}{RT} + \frac{\Delta H^\theta}{298R}\right]\right\} \qquad (20)$$

Equation 18 is obtained when the values[19] $K_{NH_4^+}\Big|_{25°C} = 1.8 \times 10^{-5}$, $\Delta H^\theta_{NH_4^+}\Big|_{25°C} = 12.57$ kcal/mole, and $R = 1.98 \times 10^{-3}$ kcal/mole °K are substituted into Equation 20.

A similar calculation may be done for K_W where $K_W\Big|_{25°C} = 1 \times 10^{-14}$. and $\Delta H^\theta_W\Big|_{25°C} = 13.34$ kcal/mole

The ratio of the ion product constant for water K_W and K_b is then

$$\frac{K_W}{K_b} = 5.56 \times 10^{-10}\left\{\exp[-388.9/(.5555\ T + 255.2) + 1.3]\right\} \qquad (21)$$

where $K_W = [H^+][OH^-]$.

VII. BASIC EQUATIONS

A. Dimensions of Countercurrent Tower

The height of a stripping tower is given by[35]

$$Z = \left(N_{OL}\right)\left(H_{OL}\right) \tag{22}$$

where N_{OL} is the number of overall liquid transfer units and H_{OL} is the height of a liquid transfer unit. The general expressions for N_{OL} and H_{OL} are

$$N_{OL} = \int_{X_2}^{X_1} \frac{(1 - X)_{mean} dx}{(1 - X)(X^* - X)} \tag{23}$$

where X is the mole fraction of solute in liquid, X* is the mole fraction of solute in solution in equilibrium with the bulk concentration of the gas, and 1 signifies "leaving" and 2 "entering" conditions and

$$H_{OL} = \frac{L}{K_L ac\ (1 - X)_{mean}} \tag{24}$$

where c is the total concentration of the liquid and $K_L a$ is the overall liquid-phase mass-transfer coefficient.

For dilute solutions for which Henry's law is applicable, it is possible to evaluate the integral which defines N_{OL}. The result is[6]

$$N_{OL} = \frac{\ln\left[\frac{X_2 - Y_1/m}{X_1 - Y_1/m}\left(1 - \frac{L}{mG}\right) + \frac{L}{mG}\right]}{1 - \frac{L}{mG}} \tag{25}$$

where m is Henry's constant, L is the liquid rate per unit area, Y the mole fraction of solute in gas, and G is the gas rate per unit area. See Figure 1.

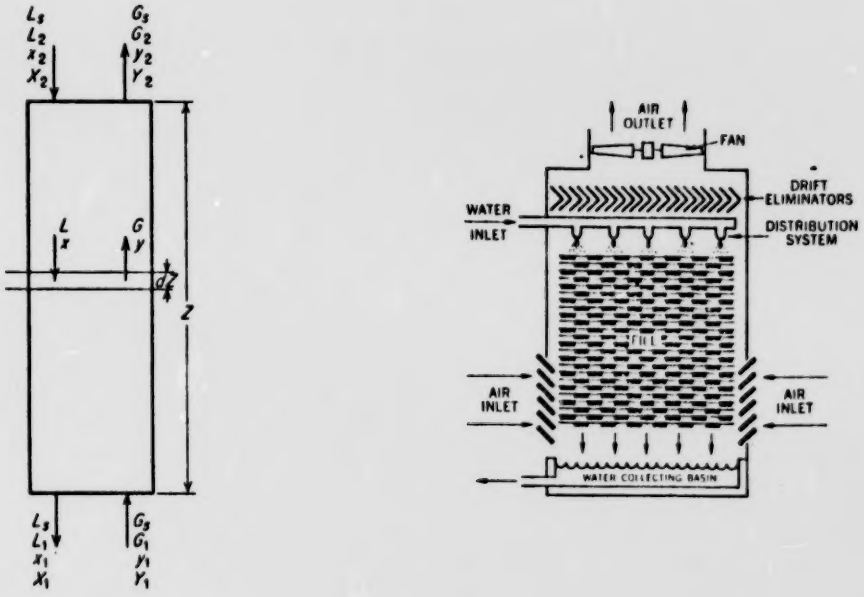

Figure 1[35]

COUNTERCURRENT TOWER

H_{OL} is an empirically determined factor and is usually expressed as a function of liquid and gas rates in the form[35]

$$H_{OL} = \gamma L^n + \beta L^q G^p \qquad (26)$$

where γ, n, β, q, and p are constants.

The cross-sectional area of the tower is determined by

$$A = L_T/L \qquad (27)$$

where L_T is the total liquid rate.

For those packings which require a steel shell, a wall thickness of 3/8 in. was chosen to be adequate[3], based on industrial practice.

B. Cost of Packing

The cost of packing is based on the volume of the tower

$$\text{Cost of packing} = C_p Z A \qquad (28)$$

where C_p is the cost of packing per unit volume of tower.

For wooden grid film packing, Sawistowski gives a value of \$1.34 for C_p. In a private communication,[18] N. W. Kelly suggested this value be increased to \$2.50 for treatment of the wood against deterioration. For splash packing, he said that the cost of the wooden splash bars and supports is \$200 per 1000 board feet. To take account treatment of the wood against deterioration, this value should be doubled. The cost of assembly is \$100 per 1000 board feet. This gives \$6.00/ft^3 of wood, or \$6.00$(1 - \varepsilon_o)$/ft^3 of tower, for the cost of splash packing where

$$\varepsilon_o = 1 - \frac{\theta_p t}{V_s}$$

in which t is the vertical thickness of a splash bar, in.

V_s is the vertical spacing of the bars, in.

θ_p is the plane solidity fraction which is equal to the horizontal thickness of the bar divided by the horizontal spacing of the bars.

For particle packing, see Table 1 for values of C_p.

All packing cost parameters are read in as data to the program, and different values may be used if applicable.

Table 1

COST DATA FOR PARTICLE PACKING
(1959 Costs, Less than 100 cu ft) [28]

	Cost, $/ft^3			
	Size, in.			
	1/2	1	1-1/2	2
Raschig rings, ceramic[b]	11.70	6.50	5.05	4.85
Raschig rings, carbon steel[e]	-	-	-	5.95
Raschig rings, stainless steel 316[e]	-	50.75	-	27.85
Raschig rings, carbon[f]	-	18.60	18.40	-
Berl saddles, ceramic[a]	24.80	9.90	7.50	7.70
Intalox saddles, ceramic[b]	23.55	9.40	7.15	7.30
Tellerettes, L. D. polyethylene[c]	-	16.00	-	-
Tellerettes, H. D. polyethylene[c]	-	18.50	-	-
Pall rings, ceramic[d]	-	5.00[g]	-	-
Pall rings, polypropylene[b]	41.00	26.00	20.75	16.50
Pall rings, stainless steel	186.50	96.00	83.00	69.00

a M. A. Knight Co.
b U.S. Stoneware Co.
c Colonial Iron Works Co.
d Bradische Anilin and Soda Fabrik.
e Johns Manville Corp.
f National Carbon Co.
g German equivalent.

C. Cost of Steel Shell for Particle Packing

The cost of the steel shell was based on weight. From the Chemical Engineers' Handbook[28]

$$\text{Weight (lb) of tower plus heads and accessories} = 170D(Z + .8D)t \quad (29)$$

where D is the tower diameter, ft.
Z is tower height, ft.
t is wall thickness, in.

$$\text{Cost of shell} = 170C_T D(Z + .8D)t \quad (30)$$

where C_T is the cost of shell per lb. C_T is equal to \$.50 for carbon steel.

D. Cost of Fan and Pump

The cost of the fan and pump can be expressed as power functions in terms of L_T and G_T according to Aries and Newton[1]

$$\text{Cost of Fan} = SG_T^{\,r} \quad (31)$$

$$\text{Cost of Pump} = aL_T^{\,b} \quad (32)$$

where S, r, a and b are constants
G_T is the total gas rate.

Aries and Newton[1] give constants which when updated to 1968 become for a centrifugal fan ($\Delta P \geq .75$ in. H_2O)

$$S = .0548 \text{ and } r = .90$$

for a propeller fan ($\Delta P < .75$ in. H_2O)

$$S = .0292 \text{ and } r = .90$$

and for an iron centrifugal pump

$$a = 14,300/(3.47 \times 10^6)^{.6}, \text{ or } 1.71$$
$$b = .60$$

E. Cost of Structure: Basin, Wiring, Supports and Distributors: Maintenance and Labor

These items can be expressed in terms of the cross-sectional area of the tower[15]

$$\text{Cost of Structure, etc.} = C_B A \qquad (33)$$
$$\text{Cost of Labor \& Maintenance} = C_{LM} A$$

Both C_B and C_{LM} are costs per unit cross-sectional area of tower.

Jackson[15] gives values for C_B and C_{LM} which when updated to 1968 become $\$23.25/ft^2$ and $\$4.84/ft^2$, respectively. These values when broken down into its components are as follows. The installed cost of the structure, which includes pond, foundations, paneling and roof, is $\$18.60/ft^2$; that of the distributor and supports is $\$2.48/ft^2$; that of the lifting beam and electrical wiring is $\$2.17/ft^2$; and the annual cost for labor and maintenance of the pumps, distributor, fans, motors, and packing is $\$4.64/ft^2$. These values agreed with a recent cost estimate for a 20,000-gpm cooling tower supplied by courtesy of the Fluor Co. For particle packings, the cost of accessories is included in the cost of the steel shell so that C_B is $\$18.60/ft^2$.

F. Power Costs

The power required to pump the liquid to the top of the tower is[30]

$$L_T Z / E_p$$

where E_p is the efficiency of the pump. E_p is approximately equal to .50 but other values can be read into the program.

The power needed for the fan to draw the air up through the tower is[30]

$$G\Delta P/E_F$$

where E_F is the efficiency of the fan. E_F is approximately equal to .50 but other values can be read into the program. ΔP is the pressure drop across the tower. Pressure-drop data have been expressed in the general form[22]

$$\frac{\Delta P}{Z} = \alpha \left(\frac{G^s}{\rho_G}\right) 10^{\beta' L} \qquad (34)$$

where α, s and β' are constants. See Tables 2, 3, and 18.

The total power is found by adding these two power requirements and multiplying by C_E, the cost of electricity per kwh. C_E is uaually equal to \$.008/kwh, but a local value may be read in.

G. Installation Costs and Amortization

The cost for installation of the equipment can be expressed as a percentage of the capital cost of an item. For the steel shell this percentage is 40%, for the packing 5%, for the fan 50%, and for the pump 40%[29]. Installation of the structure is already included in its cost.

For amortization of capital charges, the lifetime of the steel shell, packing, and structure, etc. is 20 yr and that of the fans, and pumps 15 yr. For an interest rate of 4-1/2%, the amortization factor for a lifetime of 20 yr is AMF1 = .0769 and for a lifetime of 15 yr is AMF2 = .0931. These factors are also read in.

Table 2[27]

PRESSURE-DROP EQUATION FOR PARTICLE PACKING

TYPE OF PACKING	MAT'L		NOMINAL PACKING SIZE (INCHES)										
			1/4	3/8	1/2	5/8	3/4	1	1 1/4	1 3/8	1 1/2	2	3
INTALOX SADDLES	CERAMIC	α			1.04		0.52	0.52			0.13	0.14	
		β			0.37		0.25	0.16			0.15	0.10	
RASCHIG RINGS	CERAMIC	α			1.96	1.31	0.82	0.53			0.31	0.23	0.18
		β			0.56	0.39	0.38	0.22			0.21	0.17	0.15
BERL SADDLES	CERAMIC	α			1.16		0.56	0.53			0.21	0.16	
		β			0.47		0.25	0.18			0.16	0.12	
PALL RINGS	PLASTIC	α						0.22		0.14		0.10	
		β						0.14		0.13		0.12	
PALL RINGS	METAL	α				0.43		0.15			0.08	0.06	
		β				0.17		0.15			0.16	0.12	
RASCHIG RINGS 1/32 WALL	METAL	α				1.20							
		β				0.28							
RASCHIG RINGS 1/16 WALL	METAL	α			1.59	1.01	0.80	0.53			0.29	0.23	
		β			0.29	0.39	0.30	0.19			0.20	0.14	

EQUATION

$$\Delta p = \alpha \times 10^{\beta L}\left(\frac{G^2}{\rho_G}\right) \text{ (LIMITED TO REGION BELOW FLOODING)}$$

Δp = PRESSURE DROP - INCHES OF H_2O / FT. OF PACKING

G = GAS MASS VELOCITY - LBS./SEC. FT.^{2}

L = LIQUID MASS VELOCITY - LBS./SEC. FT.^{2}

ρ_G = GAS DENSITY - LBS./FT.^{3}

α AND β = CONSTANTS

Table 3[26]

PRESSURE DROP IN WOOD GRID PACKINGS

Dimensions of grids		
Height in.	*Clearance* in.	$10^3 \times f_0$
1	0·625	18·9
2	0·625	13·7
4	0·625	8·3
8	0·625	5·7
4	1·25	2·43
8	1·25	1·79
12	1·25	1·20
4	1·75	1·73
8	1·75	1·16
12	1·75	0·95
4	2·25	0·87
8	2·25	0·68
12	2·25	0·63

Johnstone and Singh expressed their pressure drop measurements for wood grid packings by the equation

$$\Delta_p = f_0 G^{1.8}$$

where

Δ_p = pressures drop as in H_2O/ft height

G = mass velocity of air, lb/(hr)(ft^2)

The values of the constant f_0 are for 1/4 in. thick wood grids in a non-staggered arrangement with water circulating at a rate of 40 to 70 lb/hr per foot perimeter.

VIII. EVALUATION OF CONSTANTS

A. Overall Height of a Liquid Transfer Unit

The overall height of a liquid transfer unit can be expressed in terms of the individual gas and liquid transfer units, which have been determined experimentally as functions of the various physical properties of a particular packing[35]

$$H_{OL} = H_L + \left(\frac{L_M}{mG_M}\right) H_G \qquad (35)$$

where H_L is the individual height of a liquid transfer unit
H_G is the individual height of a gas transfer unit
L_M is the molar liquid rate
G_M is the molar gas rate.

1. Particle Packings

For particle packings such as saddles and rings, H_L and H_G are given by[35, 33, 26, 14]

$$H_L = .0398\left(\frac{Ld_s}{\mu_L}\right)^{.55}\left(Sc_L{}^{.5}/\emptyset a'\right) \qquad (36)$$

$$H_G = .837\left(\frac{d_s G}{\mu_G(1 - \varepsilon_o)}\right)^{.36}\left(Sc_G{}^{2/3}/\emptyset a'\right) \qquad (37)$$

where d_s is the diameter of a sphere* of the same surface as a single packing particle, μ_G and μ_L are the viscosity of the gas and liquid respectively, and Sc_G and Sc_L are the Schmidt numbers for the gas and liquid phase, ε_o is the void space in the packing, and a' is the physical surface area of the packing per unit volume of tower, and $\emptyset$ is the fraction of the packing that is actually wetted when the tower is in operation. See Tables 4 - 9 for values of these parameters.

The fraction of the surface area of the packing that is wetted has been investigated by many; however, the results of Zhavoronkov[14] are considered to be the most reliable and are represented by the equations

$$\emptyset = .0292\ a'^{1/3}\left(\frac{L}{\rho_L}\right)^{.632} \quad \text{for } \frac{L}{\rho_L} \leq 26.2\ \frac{ft}{hr} \qquad (38)$$

$$\emptyset = .0672\ a'^{1/3}\left(\frac{L}{\rho_L}\right)^{.551} \quad \text{for } \frac{L}{\rho_L} > 26.2\ \frac{ft}{hr}$$

*d_s is more conveniently given by $\sqrt{a'/\pi NUM}$ where NUM is the number of particles per unit volume of tower.

where ρ_L is the density of the liquid.

If Ø, as calculated from either of the above equations, is greater than unity, then the packing is completely wetted and Ø should be set equal to unity.

If Equations 36, 37, and 38 are substituted into Equation 35, the result may be written in the form

$$H_{OL} = \gamma L^n + \beta L^q G^p \qquad (39)$$

where

$$\gamma = .575 d_s^{.55} (SCLR)^{.5} / a' (PHI) (MULR)^{.55}$$

$$\beta = 3.465 \left(\frac{d_s}{1 - \varepsilon_o} \right)^{.36} (SCGR)^{.67} / a' (m) (PHI) (MUGR)^{.36}$$

$$n = .55 - WET$$

$$q = 1 - WET$$

$$p = .64$$

m = Henry's constant

$$\left.\begin{aligned} WET &= .632 \\ PHI &= .0292\, a'^{.33} / \rho_L^{.632} \end{aligned}\right\} \text{ for } L/\rho_L \leq 26.2$$

$$\left.\begin{aligned} WET &= .551 \\ PHI &= .0672\, a'^{.33} / \rho_L^{.551} \end{aligned}\right\} \text{ for } L/\rho_L > 26.2$$

SCLR, SCGR, MULR, and MUGR are functions which account for the effect of temperature on Schmidt numbers for liquid, gas, and viscosities for liquid and gas, respectively. (See Section VI.)

Table 4[36]

CERAMIC RASCHIG RINGS
(CHEMICAL STONEWARE AND WHITE PORCELAIN)

Size, in.	Wall thickness, in.	OD and length, in.	Approximate number per cu ft	Approximate weight per cu ft, lb*	Approximate surface area, sq ft/cu ft	Percent free gas space
1/4†	1/32	1/4	88,000	46	240	73
5/16†	1/16	5/16	40,000	56	145	64
3/8	1/16	3/8	24,000	52	155	68
1/2	3/32	1/2	10,500	54	111	63
1/2†	1/16	1/2	10,600	48	114	74
3/4	3/32	3/4	5,600	48	100	68
3/4	3/32	3/4	3,140	44	80	73
1	1/8	1	1,350	40	58	73
1 1/4	3/16	1 1/4	680	43	45	74
1 1/2	1/4	1 1/2	375	46	35	68
1 1/2†	3/16	1 1/2	385	42	38	71
2	1/4	2	162	38	28	74
2†	3/16	2	164	35	29	78
3‡	3/8	3	48	40	19	74
3(M)§	3/8	3	74	67	29	60
3(R)§	3/8	3	64	58	25	66

* Porcelain rings are about 5% heavier than stoneware. These weights are the average for both.

† Offered in porcelain only.

‡ The 4-in. OD and 6-in. OD sizes are also standard. The 3-in., 4-in., and 6-in. OD sizes are also made with ribbed or corrugated outside surfaces. The 3-in., 4-in., and 6-in. sizes can be made in lengths up to 12 in., on special order.

§ Data for stacked arrangement. M indicates diamond pattern. R indicates square pattern.

Table 5[36]

METAL RASCHIG RINGS

Size, in.	Wall thickness, in.	OD and length, in.	Approximate number per cu ft	Approximate weight per cu ft, lb*	Approximate surface area, sq ft/cu ft	Percent free gas space
¼	1/32	¼	88,000	150	236	69
5/16	1/32	5/16	45,000	120	190	75
5/16	1/16	5/16	43,000	198	176	60
½	1/32	½	11,800	77	128	84
½	1/16	½	11,000	132	118	73
19/32	1/32	19/32	7,300	66	112	86
19/32	1/16	19/32	7,000	120	106.5	75
¾	1/32	¾	3,410	55	83.5	88
¾	1/16	¾	3,190	100	71.8	78
1	1/32	1	1,440	40	62.7	92
1	1/16	1	1,345	73	56.7	85
1¼	1/16	1¼	725	62	49.3	87
1½	1/16	1½	420	50	41.2	90
2	1/16	2	180	38	31.4	92
3	1/16	3	53	25	20.6	95
3 (M)†	1/16	3	74	35	29	93
3 (R)†	1/16	3	64	30	25	94

* Weights shown are for carbon steel. Metal Raschig rings are also made in stainless steel, copper, and aluminum.

† Data for stacked arrangement. M indicates diamond pattern. R indicates square pattern.

Table 6[36]

CARBON RASCHIG RINGS

Size, in.	Wall thickness, in.	OD and length, in.	Approximate number per cu ft	Approximate weight per cu ft, lbs	Approximate surface aren, sq ft/cu ft	Percent free gas space
¼	1/16	¼	85,000	46	212	55
½	1/16	½	10,600	27	114	74
¾	⅛	¾	3,140	34	75	67
1	⅛	1	1,325	27	57	74
1¼	3/16	1¼	678	31	45	69
1½	¼	1½	392	34	37.5	67
2	¼	2	166	27	28.5	74
3	5/16	3	49	33	19	78
3(M)*	5/16	3	74	49.5	29	66
3 (R)*	5/16	3	64	43	25	71

* Data for stacked arrangement. M indicates diamond pattern. R indicates square pattern.

Table 7[36]

PALL-RING DATA

OD and length, in.	Wall thickness, gage	Approximate number per cu ft	Approximate weight per cu ft, lb (carbon steel)	Approximate surface area, sq ft/cu ft	Percent free gas space
⅝	26	7700	50	131.2	90.2
1	24	1520	33	66.3	93.4
1½	22	490	30	48.1	94.0
2	20	210	27.5	36.6	94.0

Also available in stainless steels, aluminum, and copper.

Table 8[36]

BERL-SADDLE PACKINGS

Nominal size, in.	Approximate number per cu ft	Approximate weight per cu ft, lb	Approximate surface area, sq ft/cu ft	Percent free gas space
¼	113,000	56	274	60
½	16,200	54	142	63
¾	5,000	48	82	66
1	2,200	45	76	69
1½	580	38	44	75
2	250	40	32	72

Table 9[36]

AVERAGE DATA AND SPECIFICATIONS FOR INTALOX SADDLES

Nominal size, in.	Approximate number per cu ft	Approximate weight per cu ft, lb	Approximate surface area, sq ft/cu ft	Percent free gas space
¼	117,500	54	300	75
½	20,700	47	190	78
¾	6,500	44	102	77
1	2,385	42	78	77.5
1½	709	37	59.5	81
2	265	38	36	79

Table 10[16]

MASS-TRANSFER DATA ON GRIDS

Run No.	Air Flow, G_a	Air Entering: Dry bulb	Air Entering: Wet bulb	Air Leaving: Dry bulb	Air Leaving: Wet bulb	Transfer Factor, j'	H. T. U. for SO_2	k_g	$\frac{d_e G_a}{\mu F_a}$	ν_a
	Lb./(hr.) (sq. ft.)	*° F.*	*° F.*	*° F.*	*° F.*		*Ft.*	*Lb. moles SO_2/(hr.) (sq. ft.) (atm.)*		
A.	Grids, d_g = 0.625 In.; d_e = 1.15 In.; S = 0.538 Sq. Ft.; F_a = 0.666; Wetted Perimeter, 15.05 Ft.; Water Rate = 40 Lb./(Hr.)(Ft. Wetted Perimeter)									
	Grids staggered; d_g = 1 In.; Depth of Packing = 1.67 Ft.; A = 25.04 Sq. Ft.									
1	1070	83.07	63.35	65.49	64.00	0.0294	1.00	1.36	3,520	0.00514
1a	1070	83.33	63.37	65.62	64.02	0.0287	1.02	1.32	3,520	0.00498
2	1160	80.97	58.57	61.27	59.69	0.0295	0.95	1.44	3,820	0.00510
2a	1160	81.62	58.57	61.23	59.71	0.0304	0.96	1.48	3,820	0.00525
3	1710	81.62	58.58	60.95	59.42	0.0308	0.95	2.21	5,620	0.00575
3a	1710	80.69	58.60	61.23	59.43	0.0285	1.02	2.11	5,620	0.00530
4	1815	83.07	63.52	65.78	63.86	0.0299	1.09	2.11	5,960	0.00522
4a	1815	83.03	63.60	65.74	63.85	0.0272	1.08	2.12	5,960	0.00525
5	2175	82.60	63.51	65.41	63.23	0.0296	1.10	2.49	7,150	0.00542
5a	2175	82.75	63.56	65.39	63.30	0.0296	1.10	2.49	7,150	0.00542
6	2220	81.21	58.53	61.31	59.17	0.0269	1.09	2.49	7,280	0.00523
6a	2220	81.14	58.65	61.39	59.21	0.0268	1.07	2.49	7,280	0.00523
7	2495	80.67	58.40	61.42	59.08	0.0256	1.14	2.68	8,195	0.00518
7a	2490	81.01	58.31	61.44	59.10	0.0258	1.14	2.69	8,195	0.00520
8	2540	82.28	63.19	65.49	63.23	0.0251	1.17	2.75	8,350	0.00522
8a	2540	82.56	63.34	65.55	63.31	0.0253	1.16	2.76	8,350	0.00525
									Av.	0.00525
	Grids Nonstaggered; d_g = 1 In.; Depth of Packing = 1.67 Ft.; A = 25.04 Sq. Ft.									
1	1070	88.25	66.06	67.71	65.81	0.0294	1.02	1.35	3,520	0.00511
1a	1070	84.08	66.59	67.67	65.88	0.0304	0.96	1.39	3,520	0.00525
2	1530	84.11	65.86	67.53	65.33	0.0280	1.05	1.83	5,025	0.00523
2a	1530	87.80	66.06	67.66	65.54	0.0281	1.05	1.83	5,025	0.00523
3	1840	86.74	65.08	67.16	64.80	0.0266	1.10	2.08	6,050	0.00511
3a	1840	86.38	65.25	67.15	64.73	0.0262	1.12	2.06	6,050	0.00505
4	2110	85.63	64.02	66.44	64.01	0.0247	1.18	2.24	6,990	0.00492
4a	2110	85.94	64.82	67.15	64.73	0.0257	1.14	2.34	6,990	0.00515
5	2520	84.78	63.70	66.10	63.60	0.0252	1.16	2.71	8,300	0.00519
5a	2520	85.11	63.70	66.47	63.86	0.0247	1.18	2.66	8,300	0.00510
6	2680	83.97	63.49	65.97	63.45	0.0248	1.18	2.85	8,820	0.00516
6a	2680	84.04	63.58	66.01	63.45	0.0243	1.21	2.78	8,820	0.00504
									Av.	0.00513
	Grids Nonstaggered; d_g = 2 In.; Depth of Packing = 1.67 Ft.; A = 25.04 Sq. Ft.									
1	1130	79.51	59.81	63.25	61.37	0.0253	1.16	1.24	3,110	0.00450
1a	1130	80.74	59.63	63.13	61.36	0.0266	1.10	1.30	3,110	0.00471
2	1860	79.08	59.03	63.04	60.52	0.0224	1.31	1.81	5,120	0.00438
2a	1860	79.41	59.16	63.12	60.56	0.0225	1.31	1.82	5,120	0.00440
3	2150	80.02	59.28	63.21	60.53	0.0225	1.31	2.09	7,110	0.00451
3a	2150	80.04	58.93	63.03	60.42	0.0226	1.30	2.11	7,110	0.00455
4	2530	79.61	59.14	63.11	60.30	0.0219	1.34	2.40	8,351	0.00458
4a	2530	79.89	59.40	63.20	60.38	0.0221	1.32	2.42	8,351	0.00462
5	2690	79.44	59.54	63.51	60.63	0.0213	1.37	2.51	8,880	0.00452
5a	2690	79.58	59.74	63.47	60.59	0.0217	1.35	2.54	8,880	0.00457
									Av.	0.00453
	Grids Nonstaggered; d_g = 4 In.; Depth of Packing = 2.0 Ft.; A = 30.05 Sq. Ft.									
1	1070	87.12	65.14	68.00	65.57	0.0212	1.38	0.97	3,520	0.00366
1a	1070	87.06	64.97	68.32	65.55	0.0198	1.48	0.91	3,520	0.00343
2	1510	87.70	65.68	68.56	65.62	0.0199	1.47	1.28	4,975	0.00370
2a	1510	87.36	65.65	68.60	65.68	0.0197	1.46	1.27	4,975	0.00368
3	1820	86.96	65.70	68.59	65.44	0.0191	1.53	1.55	5,980	0.00368
3a	1820	87.04	65.51	68.40	65.41	0.0195	1.51	1.51	5,980	0.00374
4	2120	86.72	65.43	68.48	65.21	0.0185	1.58	1.67	6,975	0.00367
4a	2120	86.74	65.34	68.45	65.14	0.0186	1.57	1.69	6,975	0.00372
5	2540	86.60	65.40	68.66	65.26	0.0181	1.62	1.98	8,350	0.00372
5a	2540	86.74	65.41	68.81	65.24	0.0177	1.65	1.91	8,350	0.00362
6	2750	86.55	64.88	68.59	65.11	0.0178	1.64	2.53	9,045	0.00369
6a	2760	86.74	64.80	68.81	65.14	0.0173	1.69	2.02	9,045	0.00358
									Av.	0.00366
B.	Grids, d_g = 1.25 In.; d_e = 1.98 In.; S = 0.556 Sq. Ft.; F_a = 0.763; Wetted Perimeter = 10.28 Ft.; Water Rate = 58.4 Lb./(Hr.)(Ft.)									
	Grids Nonstaggered; d_g = 4 In.; Depth of Packing = 3.33 Ft.; A = 34.3 Sq. Ft.									
1	1010	78.22	69.23	71.06	69.27	0.0164	3.08	0.65	4,990	0.00259
1a	1010	78.11	69.38	70.97	69.36	0.0174	2.90	0.68	4,990	0.00271
2	1380	83.15	72.17	75.03	72.65	0.0147	3.37	0.78	6,825	0.00242
2a	1380	83.16	71.98	74.96	72.54	0.0146	3.40	0.78	6,825	0.00242
3	1500	78.02	69.10	71.02	69.60	0.0155	3.25	0.91	7,375	0.00261
3a	1500	78.11	69.13	71.07	69.04	0.0153	3.30	0.90	7,375	0.00261
4	1850	83.23	72.04	74.96	72.45	0.0144	3.49	1.05	9,140	0.00254
4a	1850	83.79	71.92	75.17	72.35	0.0140	3.60	1.02	9,140	0.00245
5	2110	83.31	71.77	75.11	72.23	0.0134	3.76	1.12	10,400	0.00246
5a	2110	83.16	71.82	75.08	72.22	0.0134	3.76	1.12	10,400	0.00246
6	2460	77.43	68.79	71.04	68.71	0.0135	3.74	1.31	12,170	0.00255
6a	2460	77.60	69.00	71.22	68.86	0.0135	3.74	1.31	12,170	0.00255
7	2850	76.99	68.58	70.93	68.57	0.0139	3.88	1.45	14,090	0.00248
7a	2850	77.02	68.56	70.83	68.42	0.0131	3.85	1.46	14,090	0.00250
									Av.	0.00252

Run No.	Air Flow, G_s	Air Entering: Dry bulb	Air Entering: Wet bulb	Air Leaving: Dry bulb	Air Leaving: Wet bulb	Transfer Factor, H. T. U. for SO_2 j'	k_g	$d_s G_s / \mu F_s$	γ_0
	Lb./(hr.)(sq. ft.)	*° F.*	*° F.*	*° F.*	*° F.*		*Lb. moles SO_2/(hr.)(sq. ft.)(atm.)*	*Ft.*	

C. Grids, d_s = 1.75 In.; d_e = 2.58 In.; S = 0.556 Sq. Ft.; F_s = 0.807; Wetted Perimeter, 8.27 Ft.; Water Rate = 72.6 Lb./(Hr.)(Ft.)

Grids Nonstaggered; d_g = 4 In.; Depth of Packing = 4.0 Ft.; A = 33.1 Sq. Ft.

1	930	76.39	64.83	68.49	66.03	0.0151	4.40	0.52	5,675	0.00219
1a	930	76.39	67.78	68.50	66.01	0.0150	4.43	0.51	5,675	0.00211
2	1310	82.13	66.85	70.73	66.01	0.0151	4.40	0.73	7,950	0.00236
2a	1310	83.09	66.70	70.30	66.57	0.0150	4.18	0.70	7,950	0.00245
3	1350	76.68	65.02	68.76	65.91	0.0142	4.67	0.72	8,200	0.00227
3a	1350	76.88	65.00	68.67	65.86	0.0146	4.55	0.71	8,200	0.00224
4	1690	82.13	66.32	71.11	66.41	0.0135	4.91	0.86	10,310	0.00226
4a	1700	75.64	65.09	68.76	65.87	0.0130	5.13	0.81	10,390	0.00213
5	2300	76.51	65.12	68.94	65.78	0.0122	5.45	1.05	14,400	0.00210
5a	2300	75.88	65.13	69.06	65.75	0.0122	5.45	1.05	14,400	0.00210
6	2610	76.31	65.10	69.15	65.73	0.0111	5.98	1.07	15,900	0.00198
6a	2610	75.82	65.14	69.05	65.74	0.0121	5.48	1.16	15,900	0.00214
7	2840	75.10	64.98	68.80	65.58	0.0117	5.68	1.23	17,300	0.00212
									Av.	0.00219

Grids Staggered; d_g = 4 In.; Depth of Packing = 4.0 Ft.; A = 33.1 Sq. Ft.

1	1310	125.95	74.70	85.97	75.01	0.0165	4.02	0.78	7,950	0.00253
1a	1310	125.05	73.39	87.56	74.62	0.0169	3.92	0.78	7,950	0.00253
2	1650	89.46	66.93	59.98	66.83	0.0154	4.31	0.89	10,080	0.00238
3	1720	124.68	74.18	87.31	74.56	0.0149	4.45	0.94	10,450	0.00244
3a	1720	124.30	73.39	87.56	74.62	0.0148	4.48	0.94	10,450	0.00244
4	2030	123.40	73.54	88.13	74.27	0.0141	4.71	1.05	12,320	0.00238
4a	2030	123.40	73.54	87.77	74.19	0.0143	4.64	1.07	12,320	0.00242
5	2040	81.06	67.22	59.85	60.65	0.0149	4.46	1.07	12,400	0.00241
5a	2040	81.07	67.14	59.74	60.56	0.0150	4.44	1.07	12,400	0.00241
6	2380	80.78	67.62	59.26	60.08	0.0138	4.81	1.11	14,500	0.00221
6a	2380	80.82	67.35	59.13	60.36	0.0132	4.85	1.13	14,500	0.00225
7	2800	80.60	67.42	59.29	60.42	0.0138	4.81	1.36	17,090	0.00237
7a	2800	80.62	67.51	59.55	60.55	0.0138	4.81	1.36	17,090	0.00237
8	2810	122.16	73.05	88.12	73.85	0.0135	4.93	1.40	17,110	0.00242
									Av.	0.00239

Grids Staggered; d_g = 8 In.; Depth of Packing = 3.33 Ft.; A = 27.6 Sq. Ft.

1	1035	79.16	58.90	63.73	59.74	0.0203	3.27	0.76	6,290	0.00296
1a	1035	78.88	59.10	63.75	58.82	0.0203	3.27	0.76	6,290	0.00296
2	1735	78.12	58.60	64.18	59.29	0.0174	3.82	1.09	10,570	0.00281
2a	1735	77.85	58.85	64.20	59.42	0.0174	3.82	1.08	10,570	0.00278
3	2270	77.48	57.50	64.29	58.64	0.0153	4.35	1.25	13,800	0.00258
3a	2270	77.11	57.74	64.13	58.74	0.0157	4.24	1.28	13,800	0.00264
4	2530	77.12	57.96	64.46	58.85	0.0151	4.40	1.37	15,390	0.00260
4a	2530	77.13	57.72	64.09	58.55	0.0155	4.28	1.41	15,390	0.00268
5	2660	77.00	57.81	64.18	58.69	0.0154	4.31	1.47	16,200	0.00268
5a	2660	76.73	57.21	63.93	58.29	0.0151	4.40	1.45	16,200	0.00256
									Av.	0.00273

Grids Nonstaggered; d_g = 8 In.; Depth of Packing = 3.33 Ft.; A = 27.6 Sq. Ft.

1	960	77.89	58.15	63.60	59.64	0.0192	3.46	0.66	5,820	0.00272
1a	960	77.50	58.12	63.57	59.64	0.0190	3.50	0.65	5,820	0.00268
2	1710	76.67	57.98	64.08	58.94	0.0158	4.20	0.97	10,400	0.00253
2a	1710	76.20	57.96	64.04	58.93	0.0155	4.28	0.96	10,400	0.00251
3	2240	75.90	57.60	64.15	58.51	0.0144	4.61	1.16	13,600	0.00242
3a	2240	75.86	57.62	64.21	58.52	0.0143	4.64	1.15	13,600	0.00240
4	2410	75.06	57.34	64.05	58.36	0.0137	4.85	1.19	14,700	0.00236
4a	2410	75.11	57.19	63.94	58.23	0.0137	4.85	1.19	14,700	0.00236
5	2750	74.83	57.23	63.86	58.27	0.0138	4.80	1.38	16,750	0.00245
5a	2750	74.55	57.19	63.78	58.26	0.0136	4.80	1.37	16,750	0.00243
									Av.	0.00249

D. Grids, d_s = 2.25 In.; d_e = 3.25 In.; S = 0.556 Sq. Ft.; F_s = 0.815; Wetted Perimeter, 6.33 Ft; Water Rate = 95.0 Lb./(Hr.)(Ft.)

Grids Nonstaggered; d_g = 4 In.; Depth of Packing = 3.33 Ft.; A = 21.1 Sq. Ft.

1	1025	77.85	70.08	72.86	70.51	0.0194	4.50	0.74	7,700	0.00290
1a	1025	79.23	70.21	73.00	70.66	0.0218	4.01	0.83	7,700	0.00326
2	1060	77.65	64.13	68.73	64.76	0.0202	4.32	0.81	8,090	0.00308
2a	1060	77.99	64.16	68.69	64.72	0.0208	4.20	0.83	8,090	0.00316
3	1345	79.23	70.40	73.16	70.55	0.0211	4.14	1.05	10,210	0.00330
3a	1345	78.64	70.54	73.28	70.67	0.0195	4.48	0.98	10,210	0.00308
4	1800	77.55	64.71	69.14	64.82	0.0190	4.60	1.27	13,600	0.00318
4a	1800	77.77	64.79	69.19	64.82	0.0192	4.55	1.28	13,600	0.00320
5	2100	76.97	64.53	68.96	64.60	0.0185	4.73	1.44	15,910	0.00317
5a	2100	76.49	64.50	68.94	64.60	0.0178	4.90	1.38	15,910	0.00304
6	2410	76.67	64.54	68.94	64.58	0.0180	4.87	1.62	18,300	0.00321
6a	2410	76.77	64.81	69.03	64.72	0.0183	4.76	1.64	18,300	0.00325
7	2450	77.93	70.52	73.09	70.45	0.0185	4.73	1.69	18,590	0.00331
8	2870	76.33	64.56	68.86	64.62	0.0179	4.87	1.90	21,620	0.00323
8a	2870	76.29	64.42	68.85	64.59	0.0178	4.90	1.89	21,620	0.00321
9	2880	77.60	70.28	72.91	70.28	0.0180	4.87	1.94	21,810	0.00327
9a	2880	77.46	70.28	72.85	70.25	0.0181	4.83	1.94	21,810	0.00327
									Av.	0.00318

2. Film Grid Packings

Grid packings consist of rows of thin slats laid on edge and held in place by spacer bars or bolts running across the rows. The grids are stacked one on top of another with the slats in alternate grids at right angles. See Figure 2.

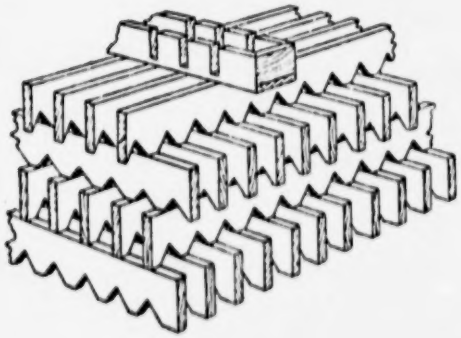

Figure 2[26]

ASSEMBLY OF SERRATED WOODEN FILM GRIDS
(The slats are 2 in. high and
spaced at 2 in. pitch.)

Johnstone and Singh[16] studied the recovery of sulfur dioxide SO_2 from waste gases using wooden film grid packing. Their data was represented by an overall gas-phase mass-transfer coefficient of the form

$$(k_G)_{SO_2} = \nu_o G^{.8} \qquad (40)$$

where ν_o is a constant which varied according to the dimensions of the grids from .00525 for 1-in.-high grids with the slats at

.625 in. spacing to .00249 for grids 8-in. high with the slats at 1.75 in. spacing. (See Table 10).

This coefficient for SO_2 absorption can be used for NH_3 stripping with a correction for the different value of diffusivity[26]

$$(k_G)_{NH_3} = (k_G)_{SO_2}\left(\frac{\mathscr{D}_{NH_3}}{\mathscr{D}_{SO_2}}\right)^{2/3}$$

$$= \left(\frac{.88}{.47}\right)^{2/3}\left(v_o G\right)^{.8} \qquad (41)$$

$$= 1.5 v_o G^{.8}$$

The overall height of a liquid transfer unit is related to the overall gas-phase mass-transfer coefficient by[35]

$$H_{OL} = \frac{L_m}{mK_G a} \qquad (42)$$

where a is the wetted surface area of the packing per unit volume of tower. For film-type grid packings this parameter can be determined from[14]

$$a = \frac{2(d_g + d_t)}{d_g(d_s + d_t)} \qquad (43)$$

where d_g is the height of a grid, d_t its thickness, and d_s the spacing between the grids as shown in Figure 3.

Figure 3
FILM GRID

If Equations 41 and 43 are substituted into Equation 42 the result may be written in the form

$$H_{OL} = \gamma L^n + \beta L^q G^p \qquad (44)$$

where

$\gamma = 0$
$n = 0$
$q = 1$
$p = -.8$
$\beta = (M_L m_o a)^{-1}$

and M_L is the molecular weight of the liquid.

3. Splash Grid Packing

Splash packings consist of wooden bars or slats arranged in horizontal rows so that the drops from each bar fall through some distance onto a bar below. See Figure 4. There have been no

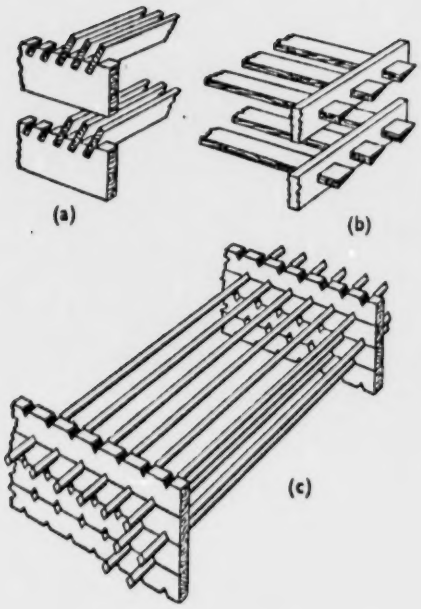

Figure 4[26]

TYPICAL SPLASH-BAR PACKINGS

studies on the performance of splash bars for stripping operation, although they are used extensively in the cooling-tower industry. Because of this lack of data, it was necessary to use somewhat uncommon means of estimation for the mass-transfer characteristics of this particular system.

a. Analogy Theory for Splash Packing

Since splash packings are used primarily for cooling towers, it was possible to find equations relating heat-transfer data to various parameters. From the analogy theory between heat and mass transfer, mass transfer coefficients were estimated. The method is as follows.

Heat-transfer data for cooling towers have been traditionally presented by investigators in the form of a parameter called the "tower characteristic" defined as $K'aZ/L$, where K' is a heat transfer coefficient based on an enthalpy driving force. Kelly and Swenson[17] correlated data for several arrangements of splash packings by the equation

$$\frac{K'aZ}{L} = .07 + AN\left(\frac{L}{G}\right)^{-n} \tag{45}$$

where N is the number of decks of packing, and A and n are constants for a given arrangement. See Table 18. The constant .07 represents the transfer above and below the packing.

Neglecting end effects and noting that

$$Z = (N - 1)V_s$$

$$\lim_{N \to \infty} Z \approx NV_s \tag{46}$$

where V_s is the vertical spacing, results in the equation

$$K'a = \frac{A}{V_s}\left[L^{1-n}G^{n}\right] \tag{47}$$

Since the Lewis number is approximately unity

$$\frac{ha}{K'aC_s} \approx 1$$

where C_s is the humid heat of air, the heat transfer coefficient, ha, based on a temperature driving force for sensible heat transfer is

$$ha = C_sK'a \tag{48}$$

By the analogy between heat and mass transfer, the mass transfer coefficient for an air-water system is[20]

$$K_G a(\text{air-water}) = \left(\frac{ha}{C_p \rho_G}\right)\left(\frac{P}{RTP_{BM}}\right)\left(\frac{Pr}{Sc}\right)^{.67} \quad (49)$$

where C_p is the specific heat, P pressure, P_{BM} log mean pressure difference, R the universal gas constant, T(°R) temperature and Pr the Prantl number. In order to use this equation for an ammonia-air-water system, a correction for the diffusivities is applied.

$$K_G a(NH_3\text{-air-}H_2O) = K_G a(\text{air-}H_2O)\left(\frac{\mathscr{D}_{NH_3}}{\mathscr{D}_{H_2O}}\right)^{2/3} \quad (50)$$

Since K_G is not strongly temperature dependent and $C_s \approx .242$, the expression $K_G a$ can be evaluated at 25°C.[20] Thus, the equation for relating the heat-transfer coefficient K'a to the mass transfer coefficient $K_G a$ is simply

$$K_G a(NH_3\text{-air-}H_2O) = 4.06 \times 10^{-2}\ K'a \quad (51)$$

The limitations on Equation 51 are that it is valid only where the gas phase resistance is controlling or where the vertical spacing between the splash bars is 1 to 2 ft. Since these restrictions limit operating conditions considerably, another approach of a purely theoretical nature may be taken which, if valid, should agree with the previous one for the case of no liquid resistance and large vertical spacing. This method of analysis is derived from the Penetration Theory and is given in the Appendix.

b. Evaluation of H_{OL} for Splash Packing

The free surface of the water in packing is made up of three main parts (Figure 5): (a) the surface of the aqueous

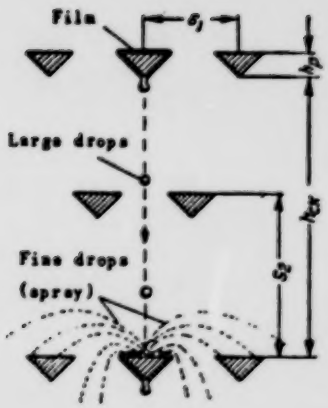

Figure 5[4]

DIAGRAM OF DISPERSION
OF WATER INTO SPRAY IN PACKING

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film formed on the slats over which the water flows during its descent; (b) the surface of the large drops which form on the lower surfaces of the slats of each row and then fall downwards; and (c) the surface of the spray (fine drops) formed on collision of the large drops with the top surfaces of the slats lower down in the tower packing.

To determine the contributions of each of these mechanisms to the height of a transfer unit, we proceed as follows.

(1) Contribution of Large Drops

From the Appendix, the gas-phase coefficient is

$$K_G = \frac{2}{RT}\sqrt{\frac{2\mathcal{D}_{SG}u}{\pi D}}$$

The relative velocity between the gas and liquid is

$$u = u_G + u_{drop}$$

where $u_{drop} = 4\sqrt{S_V}$, ft/sec

$$= 4(60)^2 \, S_V, \text{ ft/hr}$$

$$u_G = G/\rho_G, \text{ ft/hr}$$

Substituting

$$K_G = \frac{2}{RT}\sqrt{\frac{\mathscr{D}_{SG}\left[G/\rho_G + 4\sqrt{S_V}\,(60)^2\right]}{\pi D}} \tag{52}$$

From the Appendix, the liquid-phase coefficient is

$$K_L = 2\sqrt{\frac{\mathscr{D}_{SL} u_{drop}}{\pi S_V}}$$

$$= 2\sqrt{\frac{4(60)^2 \mathscr{D}_{SL}\sqrt{S_V}}{\pi S_V^{1/2}}} = 240\sqrt{\frac{\mathscr{D}_{SL}}{\pi S_V^{1/2}}} \tag{53}$$

and the surface area per unit volume of tower is

$$a = \frac{6L}{\rho_W (u_{drop}) D} = \frac{6L}{\rho_W 4(60)^2 \sqrt{S_V}\, D}$$

$$= \frac{3L}{2(60)^2 \rho_W D S_V^{1/2}} \tag{54}$$

Therefore, substituting these expressions into the equation for H_L

$$H_L = \frac{L}{\rho_W K_L a} = \left(\frac{L}{\rho_W}\right)\left(\frac{1}{120}\right)\sqrt{\frac{\pi S_V^{1/2}}{\mathscr{D}_{SL}}}\left(\frac{2(60)^2 \rho_W D S_V^{1/2}}{3L}\right)$$

$$= 10D\sqrt{\frac{\pi}{\mathscr{D}_{SL}}}\left(S_V\right)^{3/4} \qquad (55)$$

and into the equation for H_G

$$H_G = \frac{G_M}{K_G a}$$

$$= \frac{G/29}{K_G a}$$

$$= \left(\frac{G}{29}\right)\left[\frac{2(60)^2 \rho_W D S_V^{1/2}}{3L}\right]\left[\frac{RT}{2}\sqrt{\frac{\pi D}{2\mathscr{D}_{SG}\left(G/\rho_G + 4(60)^2\sqrt{S_V}\right)}}\right]$$

$$= \left(\frac{G}{29}\right)\left[\frac{2(60)^2 \rho_W D S_V^{1/2}}{3L}\right]\left[\frac{RT}{2}\sqrt{\frac{\pi D \rho_G}{2\mathscr{D}_{SG}}}\left(G + 4(60)^2 \rho_G \sqrt{S_V}^{-1/2}\right)\right]$$

$$= \frac{(60)^2 \rho_W D S_V^{1/2} RT}{87}\sqrt{\frac{\pi D \rho_G}{2\mathscr{D}_{SG}}}\left[\frac{G(G + 4(60)^2 \rho_G \sqrt{S_V}^{-1/2}}{L}\right]$$

$$\lim_{S_V \to 0} H_G = \frac{(60)^2 \rho_W D S_V^{1/2} RT}{87}\sqrt{\frac{\pi D \rho_G}{2\mathscr{D}_{SG}}}\left(G^{1/2} L^{-1}\right) \qquad (56)$$

Combining H_L and H_G into H_{OL} gives

$$H_{OL}(\text{Splash}) = \gamma_s L^{n_s} + \beta_s L^{q_s} G^{p_s} \tag{57}$$

where

$$\gamma_s = (60)^2 \frac{D}{360}\sqrt{\frac{\pi}{\theta_{SL}}}\,|S_V|^{3/4} = 10D\sqrt{\frac{\pi}{\theta_{SL}}}\,|S_V|^{3/4} \tag{58}$$

$$n_s = 0$$

$$\beta_s = \left(58.0\ \rho_W D S_V^{1/2}\right)\left(\frac{RT}{m}\right)\sqrt{\frac{\pi D \rho_G}{2\ SG}} \tag{59}$$

$$q_s = 0$$

$$p_s = -.5$$

(2) Contribution of Fine Drops and Probability of Drops Hitting a Slat

Correction factors for the gas and liquid phase coefficients are derived which account for the following two phenomena: (1) a spray or fine drops are formed when the large drops formed on the lower surfaces of the slats collide with the top surfaces of the slats lower in the tower, and (2) a drop may fall past several slots before hitting one.

From the Appendix under drop size, the average diameter of the large drops (d_L) is approximately 6.32 mm. From the data of Berman[4], the mean diameter (d_F) of the size distribution of the spray is .855 mm.

From the Penetration Theory the gas phase coefficient for the fine drops K_{GF} can be expressed in terms of K_G for the large

drops as

$$K_{GF} = \sqrt{\frac{d_L}{d_F}}\ K_G$$

$$= 2.72\ K_G$$

while the liquid phase coefficient remains the same.

To determine the surface areas of the large and fine drops, it is observed from Figure 6 that as a representative value at 15 in.

$$\frac{\%\ \text{Fine Drops}}{\%\ \text{Large Drops}} = .48$$

Since % Fine Drops + % Large Drops = 1

$$\%\ \text{Fine Drops} = .32$$

$$\%\ \text{Large Drops} = .68$$

If a is the surface area based on all drops being large, the actual surface of the large drops a_L and fine drops a_F are

$$a_L = .68a$$

$$a_F = .32\left(\frac{d_L}{d_F}\right)a = 2.37a$$

Combining these results gives the weighted coefficients

$$(K_G a)_{\text{weighted}} = K_{GF}a_F + K_G a_L$$

$$= 2.72(2.37a)K_G + .68a\ K_G = 7.13\ K_G a$$

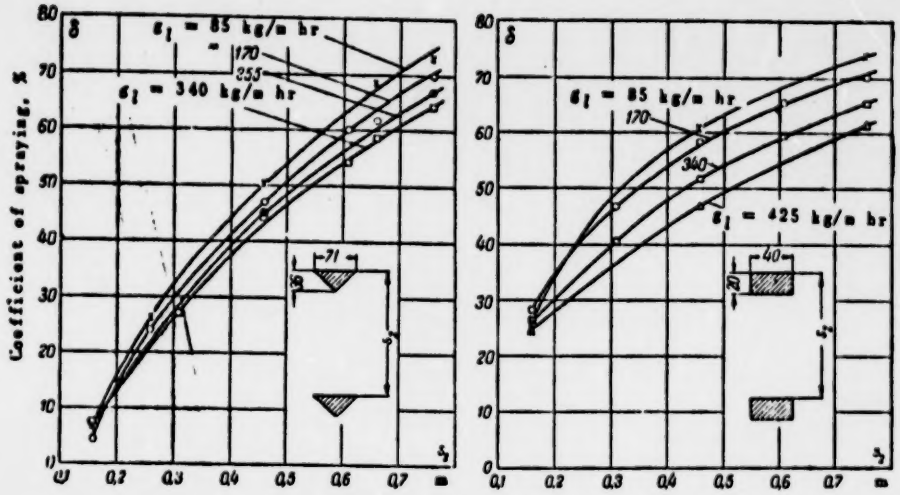


Figure 6[4]

COEFFICIENT OF DISPERSION FOR THREE- AND FOUR-FACED SLATS

$$(K_L a)_{weighted} = K_L a_L + K_L a_F$$

$$= .68\ K_L a + 2.37\ K_L a$$

$$= 3.05\ K_L a$$

From the data of Kelly and Swenson[17] the average vertical free fall of a drop is about

$$\text{Aver. Free Fall} = 3.2\ S_V$$

when S_V is about 15 in.

Since $a \propto 1/\sqrt{S_V}$, the weighted coefficients become

$$(K_G a)_{\text{weighted}} = \frac{7.13}{\sqrt{3.2}} K_G a = 4.2\, K_G a$$

$$(K_L a)_{\text{weighted}} = \frac{3.05}{\sqrt{3.2}} K_L a = 1.7\, K_L a$$

Because the curves of Figure 6 are approximately linear, the effective gas-phase transfer coefficient may be written so as to satisfy the limiting conditions

$$\lim_{S_V \longrightarrow 0} (K_G a)_{\text{eff}} = K_G a$$

$$(K_G a)_{\text{eff}} \Big|_{S_V = 15 \text{ in.}} = 4.2\, K_G a$$

as

$$(K_G a)_{\text{eff}} = (1 + \frac{3.2}{1.25} S_V)\, K_G a$$

and the effective liquid phase transfer coefficient may be written so as to satisfy the limiting conditions

$$\lim_{S_V \longrightarrow 0} (K_L a)_{\text{eff}} = K_L a$$

$$(K_L a)_{\text{eff}} \Big|_{S_V = 15 \text{ in.}} = 1.7\, K_L a$$

as

$$(K_L a)_{eff} = \left(1 + \frac{.7}{1.25} S_V\right) K_L a$$

where S_V is in feet.

Therefore, the contribution of the fine drops and the effect of the actual free fall on the overall height of a transfer unit may be included by multiplying Equation 58 by

$$\frac{1}{1 + \frac{.7}{1.25} S_V} \tag{60}$$

which corrects the liquid-phase height of a transfer unit and multiplying Equation 59 by

$$\frac{1}{1 + \frac{3.2}{1.25} S_V} \tag{61}$$

which corrects the gas-phase height of a transfer unit. This gives

$$\gamma_s = 10D \sqrt{\frac{\pi}{\mathscr{D}_{SL}}}\, S_V^{3/4} / \left(1 + \frac{.7}{1.25} S_V\right) \tag{62}$$

$$n_s = 0$$

$$\beta_s = 58.0\, \rho_W D\, S_V^{1/2} \frac{RT}{m} \sqrt{\frac{\pi D \rho_G}{2\mathscr{D}_{SG}}}\, \frac{1}{1 + \frac{3.2}{1.25} S_V}$$

$$q_s = 0$$

$$p_s = -.5$$

To check the validity of the penetration model, a calculation of the gas-phase coefficient was made for L = 1000 lb/hr ft^2.

$G = 2000$ lb/hr ft^2 and $V_S = 15$ in. The analogy gave a value of 4.6 lb mole/hr ft^2 atm for $K_G a$, while the penetration model gave a value of 4.2 lb mole/hr ft^2 atm for $K_G a$. These values are in good agreement when it is considered that these two methods of estimation are based on different approaches.

(3) Film Contribution to Mass Transfer

In cooling towers where the slats are spaced far apart, the mass transfer may be due primarily to the droplets produced by splash. In an ammonia stripping tower, where the spacing must be closer, the contribution of mass transfer from the film of water on the slats may exceed that from the splash of droplets. These two effects have to be combined into one equation.

The film contribution is given by section on film packing

$$H_{OL}\ (\text{Film}) = \beta_F L G^{-.8}$$

The splash contribution is given from the previous section

$$H_{OL}\ (\text{Splash}) = \gamma_S + \beta_S G^{-.5}$$

The reciprocal of the sum of the reciprocals of these two terms gives the total height of a transfer unit, which includes all three mechanisms

$$H_{OL}\ (\text{Total}) = \frac{H_{OL}\ (\text{Splash})\ H_{OL}\ (\text{Film})}{H_{OL}\ (\text{Splash}) + H_{OL}\ (\text{Film})}$$

$$= \left[\frac{H_{OL}\ (\text{Splash})}{H_{OL}\ (\text{Splash}) + H_{OL}\ (\text{Film})}\right] H_{OL}\ (\text{Film})$$

$$= \left[\frac{\gamma_S + \beta_S G^{-.5}}{\gamma_S + \beta_S G^{-.5} + \beta_F L G^{-.8}}\right] \beta_F L G^{-.8}$$

$$H_{OL}\ (\text{Total}) = \alpha L^n + \beta L^q G^p$$

where

$$\alpha = 0$$

$$n = 0$$

$$q = 1$$

$$p = -.8$$

$$\beta = \left[\frac{\alpha_S + \beta_S G^{-.5}}{\alpha_S + \beta_S G^{-.5} + \beta_F L G^{-.8}}\right] \beta_F \qquad (63)$$

For splash bars

$$\varepsilon_o = 1 - \frac{\theta_p\ (\text{VTH})}{(\text{VS})}$$

$$\theta_p = \frac{\text{HTH}}{\text{SH}}$$

$$a = \frac{24\,(\text{HTH} + \text{VTH})}{(\text{SH})\,(\text{VS})}$$

where the dimensions are in inches. See Figure 7 for symbols. For estimating ν_o, HS-HTH may be equated to DS and (HTH + VTH) to DG, and ν_o is found as before.

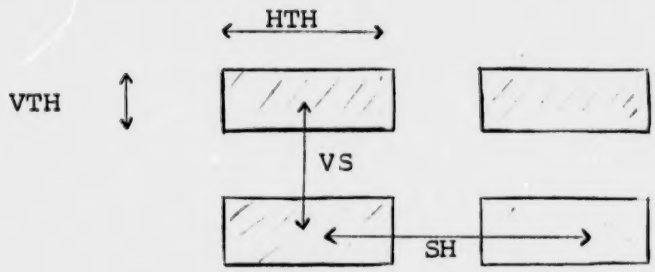


Figure 7

SPLASH BARS

B. Shell

The weight of the tower shell is given by

$$136d(Z + .8\ d)t$$

Since

$$\frac{1}{4}\pi\ d^2 = L_{T/L}$$

and $t = \frac{3}{8}$ in., the cost of the shell can be expressed as

$$COST = 170\ K_7\ C_t\ A\ B\ C\ D + 136\ K_7^2\ C_t\ E$$

where

$$K_7 = 1.13\sqrt{L}$$

$$A = 3/8\sqrt{L}$$

$$B = 1/(1 - K_4 L/G)$$

$$C = L^n + B\, L^q\, G^p$$

$$D = \ln (K_5\, L/G + K_6)$$

$$E = 3/8\, L$$

$$K_5 = 1.83\, (1 - K_6)/m$$

$$K_6 = \text{TOTNH3/NH3OUT}$$

$$K_4 = 1.83/m$$

TOTNH3 is initial concentration of NH_3, and NH3OUT is final concentration of NH_3.

C. Fan

The purchase cost of the fan is given by

$$\text{COST} = K_{10} \left(\frac{G}{L}\right)^{.9}$$

where for a centrifugal fan

$$K_{10} = .0548\, L_T{}^{.9}$$

and for a propeller fan

$$K_{10} = .0548\, (.54)\, L_T{}^{.9}$$

D. Pump

The purchased cost of the pump is given by

$$\text{COST} = 14300 \left(\frac{L_T}{3.47 \times 10^6}\right)^{.6}$$

E. Pumping Power

The cost of pumping the feed to the top of the tower is given by

$$\text{COST} = C_E K_{11} \left[\gamma L^n + \beta L^q G^p\right] \frac{\ln\left[K_5 \frac{L}{G} + K_6\right]}{1 - K_4 \frac{L}{G}}$$

where

$$K_{11} = 3.75 \times 10^{-7} \text{ (THETA) } L/E_p$$

THETA is the time of operation per year in hours (8400 hr/yr).

F. Fan Power

The cost to draw the air up through the tower is given by

$$\text{COST} = K_{12}\left(\frac{G}{L}\right)^3 10^{B'L} C_E \left[\gamma L^n + \beta L^q G^p\right] \frac{\ln\left[K_5 \frac{L}{G} + K_6\right]}{1 - K_4 L/G}$$

where

$$K_{12} = \frac{3.44 \times 10^{-4} \text{ (THETA) } L_T \alpha \text{ (RHOLR)}}{E_F \text{ (RHOGR)}^2}$$

G. Packing

The cost of the packing is given by

$$\text{COST} = \frac{C_p L_T}{L} \left[\gamma L^n + \beta L^q G^p\right] \frac{\ln\left[K_5 \frac{L}{G} + K_6\right]}{1 - K_4 \frac{L}{G}}$$

H. Structure, etc. and Labor and Maintenance

The cost of the structure, etc. is given by

$$\text{COST} = C_B L_T/L$$

and the annual cost of labor and maintenance is given by

$$COST = C_{LM} L_T / L$$

See p.15 for values of C_B and C_{LM}.

I. Evaluation of the Total Cost per Annum

All the expressions for the capital cost of each item and its installation cost are amortized and added to operating costs to give the total cost per annum. So that the tower design can be optimized, these costs are put in a single equation as follows.

$$\text{Annual Cost} = 170\, K_7 C_t (PCT) \left(K_8 L^{-1/2}\right) L^{-1/2} \left[1 - K_4\left(\frac{L}{G}\right)\right]^{-1}$$

$$\left(\gamma L^n + B L^q G^p\right) \ln\left[K_5\left(\frac{L}{G}\right) + K_6\right] + 136\, K_7{}^2 C_t (PCT) L^{-1} \left(K_8 L^{-1/2}\right) + (PCF) K_{10} \left(\frac{G}{L}\right)^r /$$

$$+ (PCPU) K_9 + C_E K_{12} G^3 L^{-1} 10^{B'L} \left(\gamma L^n + \beta L^q G^p\right) \left[1 - K_4\left(\frac{L}{G}\right)\right]^{-1} \ln\left[K_5\left(\frac{L}{G}\right) + K_6\right] /$$

$$+ C_E K_{11} \left(\gamma L^n + \beta L^q G^p\right) \left[1 - K_4\left(\frac{L}{G}\right)\right]^{-1} \ln\left[K_5\left(\frac{L}{G}\right) + K_6\right] /$$

$$+ (PCP) C_p L_T L^{-1} \left(\gamma L^n + \beta L^q G^p\right) \left[1 - K_4\left(\frac{L}{G}\right)\right]^{-1} \ln\left[K_5\left(\frac{L}{G}\right) + K_6\right]$$

$$+ (PCS) C_B L_T L^{-1} + C_{LM} L_T L^{-1}$$

The symbols that begin with the letters PC represent factors which give the annual capital cost when multiplied by the purchase cost of each item. They include a factor for installation, times the amortization factor.

$$PCT = 1.4\ AMF1$$
$$PCT = 1.5\ AMF2$$

PCPU = 1.4 AMF2

PCP = AMF1 for grid packing and 0.05 AMF1 for particle packing

PCS = AMF2

For convenience define

$$A(L) = K_8/L$$

$$B(L,G) = \left[1 - K_4\left(\frac{L}{G}\right)\right]^{-1}$$

$$C(L,G) = \gamma L^n + BL^q G^p$$

$$D(L,G) = \ln\left[K_5\left(\frac{L}{G}\right) + K_6\right]$$

$$E(L) = K_8/L^{3/2}$$

$$F(L,G) = \left(\frac{G}{L}\right)^r$$

$$H(L,G) = G^3/L$$

$$J(L) = 10^{B'L}$$

$$M(L) = 1/L$$

Then

$$\text{Annual Cost} = 170\, K_7 C_t (PCT) A(L) B(L,G) C(L,G) D(L,G)$$

$$+ 136\, K_7^2 C_t (PCT) E(L) + (PCF) K_{10} F(L,G) + (PCPU) K_9$$

$$+ C_E K_{12} H(L,G) J(L) B(L,G) C(L,G) D(L,G) + C_E K_{11} B(L,G) C(L,G) D(L,G)$$

$$+ (PCP) C_p L_T M(L) B(L,G) C(L,G) D(L,G) + (K13)(PCS)(M)$$

$$\text{where } K13 = \left(C_B + C_{LM}/PCS \right)$$

The above equation shows that the annual cost is a function only of the gas and liquid rates G and L. This is a very favorable situation, since it is possible to use direct analytical mathematics rather than guesswork to determine those values of L and G for which the annual cost is the minimum. The formal procedure is to differentiate the equation for the total annual cost with respect to L and to G. This result is in two equations; one is the slope with respect to L; and the other with respect to G. For the annual cost to be a minimum for a given set of values for L and G, this set must satisfy the criterion that these two derivatives be zero. Thus, the problem of finding the L and G which gives the least annual cost is reduced to solving two simultaneous equations in two unknowns. On the pages that follow are the equations that are generated when such a scheme is carried out.

$$\frac{\partial(\text{Annual Cost})}{\partial G} = V(L,G)$$

$$\frac{\partial(\text{Annual Cost})}{\partial L} = U(L,G)$$

$$\frac{\partial V}{G} = VG(L,G)$$

$$\frac{\partial V}{\partial L} = VL(L,G)$$

$$\frac{\partial U}{\partial G} = UG(L,G)$$

$$\frac{U}{\partial L} = UL(L,G)$$

The notation used in the computer program to represent the various derivatives of A, B, ... M is:

AL, BL ..... ML, first derivative of A ..... M with respect to L

AG, BG ..... MG, first derivative of A ..... M with respect to G

ALL ..... MLL, second derivative of A .... M with respect to L

AGG ..... MGG, second derivative of A .... M with respect to G

ALG or AGL .... MLG or MGL, derivative of A ..... M with respect to L and G.

The equations U(L,G) and V(L,G) are to be solved simultaneously for L and G. It was found that the usual simultaneous Newton-Raphson method cannot be used because the determinant of the system is nearly singular. Instead, a scheme was adopted in which L and G are separately determined, with an iteration loop for G inside an iteration loop for L. For a given L_n, the G for

which V is zero is found by iterating

$$G_{n+1} = G_n + (WTG)(DELTAG)$$

where

$$DELTAG = -V\left(L_n, G_n\right) / \frac{dV}{dG}\left(L_n, G_n\right)$$

$$WTG = G_n / \left|G_n + \backslash DELTAG \backslash\right|$$

Then for that G, the L for which U is zero is found by iterating

$$L_{n+1} = L_n + (WTL)(DELTAL)$$

where

$$DELTAL = -U\, L_n, G_n \,/ \frac{dU}{dL}\left|L_n, G_n\right|$$

$$WTL = L_n / \left|L_n + \backslash DELTAL \backslash\right|$$

Now for this value of L, the G for which V is zero is found by iterating the former equation again. This process is continued until the L and G are found for which both U and V approach zero.

IX. PROGRAM DESCRIPTION

A. Input

The program provides for reading in the parameters describing the influent air and wastewater streams. These parameters include the liquid throughput, the concentrations of ammonia in the influent and effluent wastewater, the temperature of the influent wastewater, and the wet and dry bulb temperatures of the influent air. The wastewater stream is read in by means of the stream matrix and the air stream by means of the decision

matrix. For each type of packing, the program reads in by means of the decision matrix parameters characteristic of the packings, which are used to compute mass transfer coefficients and pressure drops. For particle packings, these parameters are the number of of packings per ft^3, surface area, and the constants α, β', and S in the equation

$$\Delta P = \alpha \, 10^{\beta' L} \, G^S / \rho_G$$

For film grid packing, these parameters are the height, spacing, and thickness of the grids, α, S, and V_o in the equation

$$K_G = V_o \, G^{.8}$$

For splash grid packing, these parameters are the horizontal and vertical spacings and thicknesses of the splash bars, α and S. In addition, all the parameters for the film packing are required.

Other factors also read in by the decision matrix are amortization rates for equipment and structures, efficiencies for pumps and fans, cost of the packing, the cost of electricity, and the time of operation. This information, which is to be read in by the user, is conveniently summarized in Tables 11-13. The user has the option of permitting the program to find the optimum flow rates by reading in OPT equal to 1 or of bypassing the optimization procedure and reading in his own flowrates by reading in OPT equal to 0.

B. Output

Based upon a specified input list, as described in the previous section, the program determines the design which yields the least total cost per annum. These design variables are the

Table 11

TYPICAL INPUT DATA VALUES FOR PARTICLE PACKING

Matrix Element	Variable Name	Descriptive Parameter	Typical Input Value
SMATX (1,1)		Liquid throughput, mgd	10.
SMATX (1,2)	NH3OUT	Effluent concentration, mg/l NH_3	1.
SMATX (2,1)	TOTNH3	Feed concentration, mg/l NH_3	40.
SMATX (2,2)	--	--	--
SMATX (3,1)	TE	Feed temperature, °F	70.
SMATX (3,2)	--	--	--
DMATX (1,1)	AP	Surface area of packing	36.
DMATX (1,2)	CE	Cost of electricity, $/kwh	.008
DMATX (2,1)	EO	Fraction of free gas space	.79
DMATX (2,2)	AMF1	Amortization factor for equipment	.08
DMATX (3,1)	BETAL	β' in pressure drop eq. $\Delta P = 10^{\beta' L_G S/\rho_G}$	.10
DMATX (3,2)	AMF2	Amortization factor for structures	.096
DMATX (4,1)	ALPHAL	α in pressure drop eq.	.14
DMATX (4,2)	THETA	Time of operation, hr/yr	8400
DMATX (5,1)	S	S in pressure drop eq.	2.
DMATX (5,2)	--	--	--
DMATX (6,1)	CPA	Cost of packing, $/ft^3	7.5
DMATX (6,2)	--	--	--
DMATX (7,1)	EP	Efficiency of pump	.5
DMATX (7,2)	--	--	--
DMATX (8,1)	EF	Efficiency of fan	.5
DMATX (8,2)	--	--	--
DMATX (9,1)	NUM	Number of packings per ft^3	265.
DMATX (9,2)		--	--

Table 11 (continued)

Matrix Element	Variable Name	Descriptive Parameter	Typical Input Value
DMATX (10,1)	TDB	Dry bulb temperature of entering air, °F	95.
DMATX (10,2)	--	--	--
DMATX (11,1)	TWB	Wet bulb temperature of entering air, °F	65.
DMATX (11,2)	--	--	--
DMATX (12,1)		Type of packing -- determines which is used	1.
DMATX (12,2)	--	--	--
DMATX (13,1)	--	--	--
DMATX (13,2)	--	--	--
DMATX (14,1)	--	--	--
DMATX (14,2)	--	--	--
DMATX (15,1)	--	--	--
DMATX (15,2)	--	--	--
DMATX (16,1)	--	--	--
DMATX (16,2)	--	--	--

Table 12

TYPICAL INPUT DATA VALUES FOR FILM PACKING

Matrix Element	Variable Name	Descriptive Parameter	Typical Input Value
SMATX (1,1)	--	Liquid throughput. mgd	10.
SMATX (1,2)	NH3OUT	Effluent concentration mg/l NH_3	1.
SMATX (2,1)	TOTNH3	Feed concentration mg/l NH_3	40.
SMATX (2,2)	--	--	--
SMATX (3,1)	TE	Feed temperature. °F	70.
SMATX (3,2)	--	--	--
DMATX (1,1)	VO	V_O in the eq. $K_G = V_O G^{.8}$	.00219
DMATX (1,2)	CE	Cost of electricity $/KWH	.008
DMATX (2,1)	DG	Height of grids. in.	4.
DMATX (2,2)	AMF1	Amortization factor for equipment	.08
DMATX (3,1)	DSP	Spacing of grids. in.	1.75
DMATX (3,2)	AMF2	Amortization factor for structures	.096
DMATX (4,1)	ALPHAL	α in pressure drop eq.	1.73×10^{-8}
DMATX (4,2)	THETA	Time of operation. hr/yr	8400
DMATX (5,1)	S	S in pressure drop eq.	1.8
DMATX (5,2)	--	--	--
DMATX (6,1)	CPA	Cost of packing. $/ft^3	2.5
DMATX (6,2)	--	--	--
DMATX (7,1)	EP	Efficiency of pump	.5
DMATX (7,2)	--	--	--
DMATX (8,1)	EF	Efficiency of fan	.5
DMATX (8,2)	--	--	--

Table 12 (continued)

Matrix Element	Variable Name	Descriptive Parameter	Typical Input Value
DMATX (9,1)	DT	Thickness of grids, in.	.25
DMATX (9,2)	--	--	--
DMATX (10,1)	TDB	Dry bulb temperature of entering air, °F	95.
DMATX (10,2)	--	--	--
DMATX (11,1)	TWB	Wet bulb temperature of entering air (°F)	65.
DMATX (11,2)	--	--	--
DMATX (12,1)	TYPE	Type of packing - determines which is used	2.
DMATX (12,2)	--	--	--
DMATX (13,1)	--	--	--
DMATX (13,2)	--	--	--
DMATX (14,1)	--	--	--
DMATX (14,2)	--	--	--
DMATX (15,1)	--	--	--
DMATX (15,2)	--	--	--
DMATX (16,1)	--	--	--
DMATX (16,2)	--	--	--

Table 13

TYPICAL INPUT DATA VALUES FOR SPLASH PACKING

Matrix Element	Variable Name	Descriptive Parameter	Typical Input Value
SMATX (1,1)	--	Liquid throughput mgd	10.
SMATX (1,2)	NH3OUT	Effluent concentration mg/l NH_3	1.
SMATX (2,1)	TOTNH3	Feed concentration mg/l NH_3	40.
SMATX (2,2)	--	--	--
SMATX (3,1)	TE	Feed temperature, °F	70.
SMATX (3,2)	--	--	--
DMATX (1,1)	VS	Vertical spacing of splash bars. in.	2.
DMATX (1,2)	CE	Cost of electricity. $/ kwh	.008
DMATX (2,1)	--	--	--
DMATX (2,2)	AMF1	Amortization factor for equipment	.08
DMATX (3,1)	--	--	--
DMATX (3,2)	AMF2	Amortization factor for structures	.096
DMATX (4,1)	ALPHAL	α in pressure drop eq.	4.0×10^{-9}
DMATX (4,2)	THETA	Time of operation, hr/yr	8400.
DMATX (5,1)	S	S in pressure drop eq.	2.0
DMATX (5,2)	--	--	--
DMATX (6,1)	--	Cost of packing, $/solid ft^3	6.
DMATX (6,2)	--	--	--
DMATX (7,1)	EP	Efficiency of pump	.5
DMATX (7,2)	--	--	--
DMATX (8,1)	EF	Efficiency of fan	.5
DMATX (8,2)	--	--	--

Table 13 (continued)

Matrix Element	Variable Name	Descriptive Parameter	Typical Input Value
DMATX (9,1)	VTH	Vertical thickness of splash bars, in.	7/8 = .875
DMATX (9,2)	--	--	--
DMATX (10,1)	TDB	Dry bulb temperature of entering air, °F	95.
DMATX (10,2)	--	--	--
DMATX (11,1)	TWB	Wet bulb temperature of entering air, °F	65.
DMATX (11,2)	--	--	--
DMATX (12,1)	TYPE	Type of packing - determines which is used	3.
DMATX (12,2)	--	--	--
DMATX (13,1)	HTH	Horizontal thickness of splash bars, in.	3/8 = .375
DMATX (13,2)	--	--	--
DMATX (14,1)	VO	V_O in the eq. $K_G = V_O G^{.8}$	.003
DMATX (14,2)	--	--	--
DMATX (15,1)	SHREF	Reference SH given in Table 18	1 1/8 = 1.125
DMATX (15,2)	--	--	--
DMATX (16,1)	SH	Horizontal spacing of splash bars, in.	3.
DMATX (16,2)	--	--	--

Capital Costs	Symbol in Program
Cost of Metal Shell, $	SHELL
Cost of Fan, $	FAN
Cost of Pump, $	PUMP
Packing Cost, $	PACK
Structure Cost, $	STRUCT
Total Capital Cost, $	CAP
Debt Service in ¢/1000 gals.	DETPG
Annual Operating and Maintenance Costs	
Cost of Fan Power per Year, $	FANPOW
Pumping Power Cost per Year, $	PUMPOW
Chemical Cost (Scale Formation, etc.) per Year and Labor and Maintenance Cost per year, $	LM
Total Operating Cost/Year, $	OP
Operating Cost in ¢/1000 gals	OPPG
Total Costs in cents/1000 gals.	ACPG

Figure 8

FORMAT ADAPTED FOR CALCULATING
THE COST BREAKDOWN BY THE PROGRAM

Table 14

COMPUTER PROGRAM OUTPUT

Descriptive Parameter	Fortran Name	Units
Installed cost of metal shell	SHELL	$
Installed cost of fan	FAN	$
Installed cost of pump	PUMP	$
Cost of fan power	FANPOW	$
Cost of pumping power	PUMPOW	$
Installed cost of packing	PACK	$
Installed cost of structure	STRUCT	$
Chemical, labor, and maintenance cost	LM	$
Total capital cost	CAP	$
Type of packing	TYPE	Dimensionless
Total operating cost	OP or OPPG	$/yr or ¢/1000 gal
Debt service	DETPG	¢/1000 gal
Throughput	--	mgd
Feed temperature	T	°F
Temperature of leaving water	TB	°F
Dry bulb temperature	TDB	°F
Wet bulb temperature	TWB	°F
Mass flowrate of liquid per unit area	LP	lb/ft^2 hr
Mass flowrate of gas	GP	lb/ft^2 hr

Table 14 (cont.)

Descriptive Parameter	Fortran Name	Units
Height of tower	Z	ft
Cross-sectional area of tower	AREA	ft^2
Pressure drop	DELTAP	in. of water
Annual cost	AC	$/yr
Annual cost	ACPG	¢/1000 gal
Required entering pH	MINPH	Dimensionless
Maximum pH drop	MPHDRP	Dimensionless

In addition, the subroutine OPTIM prints the following information for each look as it iterates to find the optimum design.

Total annual cost, $	AC
Derivative of AC with respect to LP	U
Derivative of AC with respect to GP	V
Derivative of U with respect to LP	UL
Derivative of V with respect to GP	VG
Mass flowrate of liquid per unit area, lb ft^2 hr	LP
Mass flowrate of gas per unit area, lb/ft^2 hr	GP

operable pH, the liquid and gas flow rates per ft^2 (LP and GP), the height and diameter of the tower, the cost, and how it is distributed among the installed costs of the structure, packing, fan and pump, and the power costs of the fan and pump. See Figure 8.

Other factors of interest are pressure, temperature, and pH drops across the tower, and the temperature profile of liquid in the tower. As a precautionary measure, the derivatives of the total annual cost with respect to the flow rates are also printed out to be sure that the program does indeed find the optimum design. These derivatives must approach zero as the program proceeds.

C. Sample Problem

1. Statement of Problem

It is desired to design the most economical tower that can strip ammonia from 10 million gallons of wastewater per day at 70°F. The initial concentration of 40 mg/l is to be lowered to 1 mg/l of NH_3. Three representative packings are to be considered. They are 2-in. Intalox saddles representing particle packing; film grids 4-in. high, 1/4-in. thick, and spaced 1.75 in. representing film packing; splash packing of type C and D of Figure 14 with a vertical spacing of 2-in., horizontal spacing of 3-in., vertical thickness of 7/8 in., horizontal thickness of 3/8 in. The physical parameters describing these packings are given in Table 13. (ALPHAL = 4×10^{-9}, S = 2, v_0 = .003, HSREF = 1.125). Ambient wet and dry bulb temperatures are 65°F and 95°F, respectively. Equipment is to be amortized at 5% and 15 yr, structures at 5% and 20 yr. (AMF1 = .08, AMF2 = .096). The efficiency of the fans and pumps is 50%. Electricity costs $.008/kwh. The tower is to be operated 8400 hr/yr.

2. Solution and Comments

Table 15 shows that film packing gives the most economic design for the conditions of this problem. Particle packing is not feasible because although it has a high mass-transfer coefficient, the packing is expensive and has a high pressure drop. A tower with splash packing is costly because this packing gives a low mass-transfer coefficient. This is due to the small mass-transfer area of the drops compared to the area provided by the grids of film packing. Although K_G for splash packing is larger than that for film packing, the product $K_G a$ for splash packing is much smaller than that for film packing.

The conclusion that film packing is the most satisfactory packing for ammonia stripping is partially substantiated by industry's extensive use of film packing for the scrubbing of SO_2, a process very similar to ammonia stripping.

Table 15

OPTIMIZED COUNTERCURRENT TOWER DESIGNS GIVEN BY COMPUTER PROGRAM

Characteristic Parameter	Packing		
	Particle	Film	Splash
Throughput, mgd	10	10	10
Optimum liquid flow rate, lb/hr ft^2	129.0	669.4	414.2
Optimum gas flow rate, lb/hr ft^2	530.6	2,744.0	1,526.5
Height, ft	20.1	18.3	32.6
Cross-sectional area, ft^2	26,891	5,183	8,377
Pressure drop, in. H_2O	8.12	0.49	.61
Required pH	10.86	10.86	10.86
pH drop	.26	.26	.26
Outlet liquid temperature, °F	65	65	65
Installed cost of steel shell (particle packing only), $	1,381,608	none	none
Installed cost of centrifugal fan, $	223,894	226,990	202,500
Installed cost of pump, $	20,019	20,019	20,019
Packing cost, $	4,264,664	235,357	91,588
Structure cost, $	495,463	121,648	195,002
Total capital cost, $	6,385,647	604,015	509,111
Debt service, ¢/1000 gal	14.95	1.55	1.34
Annual fan power cost, $/yr	404,392	23,977	26,887
Annual pumping power cost, $/yr	3,555	3,147	5,820

Table 15 (continued)

Characteristic Parameter	Packing		
	Particle	Film	Splash
Annual chemicals, labor, and maintenance cost, $/yr	124,777	24,051	38,873
Total operating cost, $/yr	532,724	51,174	71,580
Total operating cost, ¢/1000 gal	15.24	1.46	2.05
Total cost, ¢/1000 gal	30.19	3.01	3.39

Note: Structure includes the pond, supports, distributors, foundations, roof, paneling, lifting beam, and wiring. Effect of head on pump cost is considered to be negligible.

Warning: It must be borne in mind that the design results from this example are not universal and will vary from one set of operating conditions to another. Therefore, they should not be used for extrapolating to different situations.

CROSS-FLOW TOWER

It has been suggested that cross-flow towers in which the air and water flow perpendicular to each other may be more economical than countercurrent towers for ammonia stripping, since cross-flow towers allow use of a larger volume of air at a lower fan power consumption. For this reason, the ammonia stripping tower being built at Lake Tahoe is of cross-flow design.

Design procedures for cross-flow stripping towers have not been previously developed. Thus, it was necessary to develop a model from which design equations could be derived.

I. DIMENSIONS OF TOWER AND EXIT TEMPERATURE OF LIQUID

In this derivation it will be assumed that steady state has been reached, the flow rates are constant, diffusional effects are negligible, and the mass-transfer coefficient is constant. Consider the differential element of volume in Figure 9. The mass gained by the gas is equal to

$$G_M \left(\frac{\partial C_G}{\partial x}\right) dx\, dy\, dz \tag{64}$$

where G_M is the molar gas flow rate and C_G the concentration of the gas. The mass lost by the liquid is equal to

$$-L_M \left(\frac{\partial C_L}{\partial z}\right) dz\, dx\, dy \tag{65}$$

where L_M is the molar liquid rate and C_L is the concentration of the liquid. The mass interchange is set equal to

$$K_G a(C^* - C_G)dx\, dy\, dz$$

where C^* is the gas concentration in equilibrium with the bulk

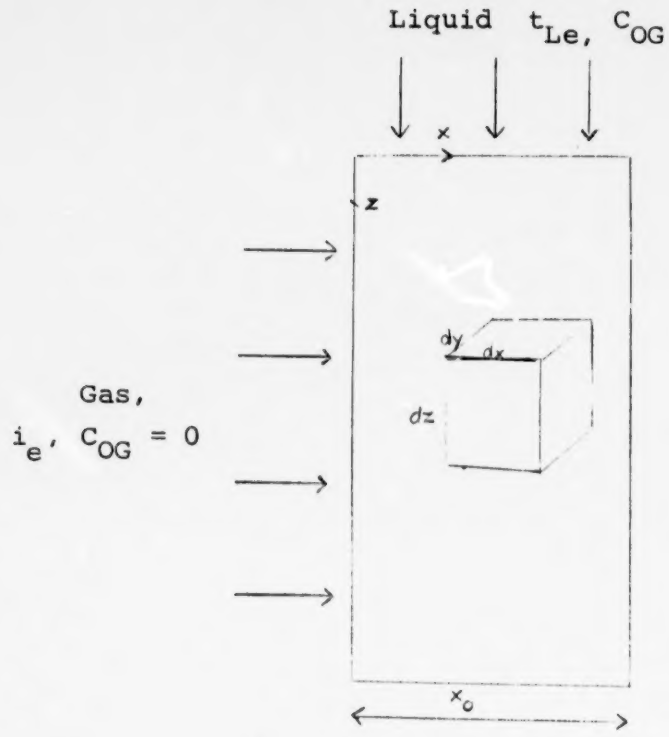


Figure 9

SCHEMATIC CROSS-FLOW TOWER

liquid concentration and $K_G a$ the overall gas-phase mass-transfer coefficient.

If Henry's Law is valid, this becomes

$$K_G a(mC_L - C_G) \tag{66}$$

where m is Henry's constant.

Since the quantities expressed by Equations 64, 65, and 66 are all equal, the governing set of equations becomes

$$-L_M\left(\frac{\partial C_L}{\partial z}\right) = K_G a\left(mC_L - C_G\right) = G_M\left(\frac{\partial C_G}{\partial x}\right) \tag{67}$$

with boundary conditions

$$C_L = C_{OL} \quad \text{at} \quad z = 0, \text{ for all } x \tag{68a}$$

$$C_G = C_{OG} = 0 \quad \text{at } x = 0, \text{ for all } z \tag{68b}$$

Using traditional mass-transfer units, flow rates are expressed in lb mole/ft^2 hr, concentrations in mole fraction, $K_G a$ in lb mole/ft^3 hr atm, and m is dimensionless.

From the paper of Farrell, et al.[8] Henry's constant for the ammonia-air-water system is a function of temperature and may be expressed as

$$m = .10 \exp(.0284\ t) \tag{69}$$

where

t is temperature, °F.

This indicates that if there were a significant liquid temperature variation in the tower, the mass-transfer equations given above would have to be solved simultaneously with similar equations governing the heat transfer due to humidification. This was done, and it was found that the results of such calculations did not differ significantly from those for which the liquid was assumed to be at the wet bulb temperature of the entering air throughput the tower. (e. g. For the example problem on p.76 and trial no. 1 on p.78 , the heights calculated by the two methods differed by 3.5%.) Solution of Equations 67 and 68 yields the concentration of the liquid in the tower from which the tower may be sized for a given separation. The solution with the wet bulb temperature as the design temperature is derived in the Appendix and is

$$Z = \frac{29L}{18mG} \frac{x_1}{1 - \exp\left[-\left(\frac{29K_G a}{G}\right)x_1\right]} \ln\left(\frac{C_{OL}}{C_{L,\,mean}}\right) \tag{70}$$

where

C_{OL} = the entering liquid concentration

$C_{L,mean}$ = the exit mean liquid concentration

m = .10 exp (.0284)(TWB)

TWB = wet bulb temperature of entering air

x_o = width of the tower

z = height of the tower

This equation may be used to calculate either the height or width of the tower once the other has been set.

For the type of cross-flow tower shown in Figure 10 and 11, the length of the tower is given by

$$y = \frac{L_T}{2x_o L} = \text{LENGTH in program} \qquad (71)$$

II. TRANSFER COEFFICIENTS

Splash-bars packing is the type that has been used for cross-flow cooling towers and for the ammonia stripping tower at Lake Tahoe. As discussed in Part I, the transfer coefficient for splash packing consists of a contribution from the liquid film on the bars and from the falling drops. Calculations based on the equations of Section VIII show that for the large (1-2 ft) vertical spacing of the splash bars used in cooling towers, the contribution of the film action is negligible; on the other hand, for the close vertical spacing required for ammonia stripping (2-4 in.), the contribution of the drops is negligible. Therefore, the mass-transfer coefficient can be found from the film coefficient as given in Section VIII.

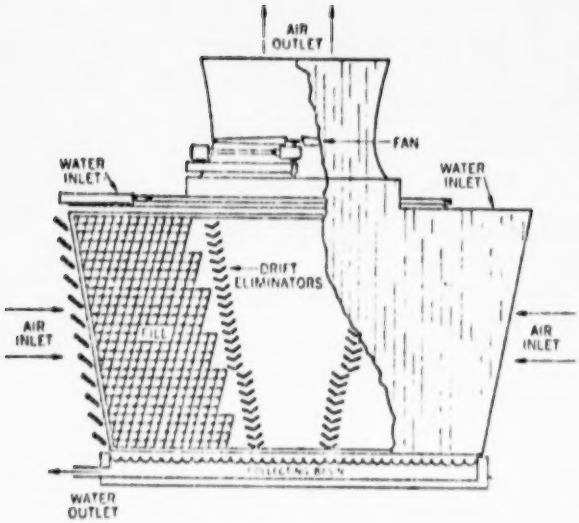


Figure 10[7]

CROSS-FLOW TOWER

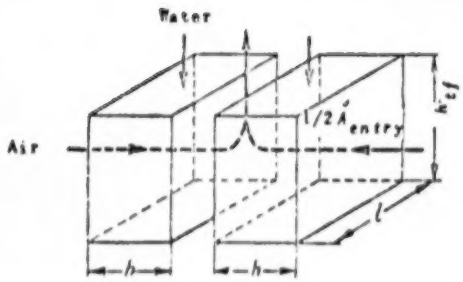


Figure 11[4]

DIAGRAM OF SPLIT FLOW PACKING

$$K_G a = 1.5\, v_0\, G^{.8}\, a$$

where $a = 24\,(HTH + VTH)/(SH)(VS)$ $\quad ft^2/ft^3$

as given in Section VIII.

By the analogy given in Section VIII, the enthalpy transfer coefficient is

$$Ka = 24.6\, K_G a$$

III. PRESSURE DROP

The pressure-drop correlation given by Kelly and Swenson[17] may be used for cross-flow towers by rotating the deck configurations of Figure 14 through 90 degrees. The effect of the vertical spacing can be estimated by using a linear relationship.[4] This gives the pressure drop (in. H_2O) across the tower as

$$\Delta P = 12B \left(\frac{.0675}{\rho_G}\right)\left(\frac{VSREF}{VS}\right)\left(\frac{x_0}{HS}\right) G^2$$

where VSREF is the spacing (perpendicular to the gas flow) for which the correlation was determined.

IV. COSTS

The cost of the various items may be readily obtained from Part I. For convenience, they have been simplified and summarized here.

A. Fan

The installed cost for a centrifugal fan ($\Delta P \geq .75$ in. H_2O) is

$$FAN = 1.5(.0548)\ G_T^{.9}$$

for a propeller fan ($\Delta P < .75$ in H_2O)

$$FAN = 1.5(.0292)\ G_T^{.9}$$

where the factor 1.5 accounts for installation.

B. Pump

The installed cost of the pump is

$$PUMP = 1.4(1.71)L_T^{.6}$$

C. Packing

The installed cost of the packing is

$$PACK = (\text{Packing cost per unit volume})\ (\text{Volume of tower})$$

The packing cost per unit volume is

$$CP = (CPS)(HTH)(VTH)/(SH)(VS)$$

where CPS is the cost of packing per solid unit volume for which Kelly[17] gives the value $6.

The volume of the tower is

$$VOL = 2x_0\ z\ y$$

D. Structure, etc.

The cost of structure, etc. is

$$STRUCT = 23.25(2)(y)(x_0)$$

E. Capital Cost

The total capital cost is

$$CAP = FAN + PUMP + PACK + STRUCT$$

F. Debt Service

Debt service per 1000 gal of feed is

$$DETPG = \left[(AMF2)(FAN) + (AMF2)(PUMP) + (AMF1)(PACK) + (AMF2)(STRUCT)\right](833800) / (L_T)(THETA)$$

G. Fan Power

The cost of the power for the fan is

$$FANPOW = 1.95 \times 10^{-6}(CE)(THETA)(G_T)\left[\Delta P/(E_F)(\rho_G)\right]$$

H. Pumping Power

The cost of the power for the pump is

$$PUMPOW = 3.75 \times 10^{-7}(L_T)(THETA)(CE)(Z)/E_p$$

I. Chemical, Labor and Maintenance Cost

The cost of chemicals, labor and maintenance is

$$LM = 4.64\left[L_T/L\right]$$

J. Total Operating Cost

The total operating cost is

$$OPER = FANPOW + PUMPOW + LM$$

or in ¢/1000 gal

$$OPPG = (OPER)(833700)/(L_T)(THETA)$$

K. Total Cost

The total cost in ¢/1000 gal is

$$ACPG = DETPG + OPPG$$

V. pH REQUIREMENT

As discussed in Part I, Section II, for a sufficient fraction of ammonia to be in molecular form, it is sufficient that the pH in the entering stream be

$$MAXPH = \log(1/HCON)$$

where

$$HCON = (1 - FRACT)(KWKB)/FRACT$$

$$KWKB = 5.56 \times 10^{-10} \exp(-388.9/(.5555*TWB + 255.2) + 1.3)$$

$$FRACT = (CO - CEX)/CO$$

VI. COMPUTER PROGRAM

A. Computer Input

Values of the following variables are required to be read in.

Fortran Name	Variable
CEX	required liquid exit concentration, any units
CO	entering liquid concentration, any units
LP	liquid flow rate, lb/hr ft^2
GP	gas flow rate, lb/hr ft^2
XE	width of tower, ft
TE	entering liquid temperature
VO	v_o in transfer coefficient equation
TWB	wet bulb temperature of entering air
Q	total liquid throughput, million of gal/day
AMF1, AMF2	amortization factors
ALPHA	B in pressure-drop equation
HTH	horizontal thickness of splash bars, in.
VTH	vertical thickness of splash bars, in.
SH	horizontal spacing of splash bars, in.
VS	vertical spacing of splash bars, in.
VSREF	reference VS
EF	efficiency of fan
EP	efficiency of pump
PCTIME	fraction of year tower is operated
CE	cost of electricity, $/kwh
CPS	$ per solid volume

B. Computer Output

Values of the following items are printed out.

Capital Costs

	Symbol in Program
Cost of Fan ($)	FAN
Cost of Pump ($)	PUMP
Packing Cost ($)	PACK
Structure Cost ($)	STRUCT
Total Capital Cost ($)	CAP
Debt Service in ¢/1000 gals.	DETPG

Annual Operating and Maintenance Costs

Cost of Fan power per year ($)	FANPOW
Pumping Power cost per year ($)	PUMPOW
Chemical cost (scale formation, etc.) per year and labor and maintenance cost per year	LM
Total operating cost/year ($)	OPER
Operating cost in ¢/1000 gals.	OPPG
Total costs in ¢/1000 gals.	ACPG

Dimensions of Tower

Height (ft)	Z
Width (ft)	XE
Length (ft)	LENGTH
Volume (ft^3)	VOL

Other Data

Exit Liquid Temperature (°F)	TOUT
lbs air/lbs water	G/L
Pressure Drop (in. H_2O)	DELTAP
Entering pH Required	MAXPH

C. Optimization Procedure

The program for designing a cross-flow tower by intent does not determine the optimum design as is done by the program for countercurrent towers. The user must find by trial and error the set of values for the liquid and gas flow rates (LP and GP), width of tower (XE), and vertical and horizontal spacing of the splash bars (VS, HS) for which the total cost is a minimum for a particular packing. The method is demonstrated by the following example.

Example Problem: It is desired to design the most economical cross-flow tower that can strip ammonia from 10 million gallons of wastewater per day entering at 70°F. The initial concentration of 40 mg/l is to be lowered to 1 mg/l NH_3. The packing chosen is of type C and D of Figures 13 and 14 (ALPHA = 4×10^{-9}, v_0 = .003, CPS = 6). The ambient wet bulb temperature is 60°F. Equipment is to be amortized at 5% and 15 yr, structures at 5% and 20 yr. (AMF1 = .08, AMF2 = .096). Take 50% as the efficiency of the fans and pumps. Electricity costs $.008/kwh. The tower is to be operated 96% of the time.

Solution: The solution is illustrated by the computer output on the following pages. The procedure is to vary one variable at a time while holding the others constant until the total cost is minimized for that variable and then doing likewise for the next variables. This method may be justified on the grounds that the total cost is somewhat insensitive over certain ranges of the operating variables. The variables to be optimized are the gas and liquid flow-rates, vertical and horizontal spacings of the splash bars, and the width of the tower. The initial values used were gas rate of 2400 lb/hr ft^2, liquid rate of 600 lb/hr ft^2, vertical spacing of 1.5 in., horizontal spacing of 2 in., and a width of 10 ft.

Table 16

INPUT LIST FOR EXAMPLE PROBLEM
FOR CROSS-FLOW VARIABLE

Variable	Value
CEX	1
CO	40
TE	70
VO	.003
TWB	60
Q	10
AMF1	.08
AMF2	.096
ALPHA	4.E-9
HTH	1.5
VTH	.375
VSREF	1.125
EF	.5
EP	.5
PCTIME	.96
CE	.008
CPS	6.00
GP	To be optimized
LP	To be optimized
VS	To be optimized
SH	To be optimized
XE	To be optimized

Table 17

OUTPUT FOR EXAMPLE PROBLEM FOR CROSS FLOW

Trial No.	Tower Width (XE)	Horizontal Spacing (SH)	Vertical Spacing (VS)	Liquid Rate (LP)	Gas Rate (GP)	¢/1000 gal
1	10	2	1.5	600	2400	6.86
2	-				1000	4.68
3					500	5.55
4				500	1000	4.86
5				500	1500	5.20
6				1000	1500	4.71
7			3.0	600	1000	4.10
8			6.0			4.33
9		1	3.0			4.68
10		5				4.58
11	5	1				4.10
12	4					4.26
13	15					4.51
14	7	2	3.0	600	1000	3.99

Figure 12

OPTIMUM DESIGN FOR EXAMPLE PROBLEM FOR CROSS FLOW

Dimensions of Tower

Width	=	7.
Height	=	57.44
Length	=	413.09
Volume	=	332249.61

Capital Costs

Cost of Fan	=	666195.38
Cost of Pump	=	20105.82
Packing Cost	=	186890.40
Structure Cost	=	134462.49
Total Capital Cost	=	1007654.11

Debt Service in Cents/1000 Gals	=	2.67

Annual Operating and Maintenance Cost

Cost of Fan Power	=	9061.38
Pumping Power Cost	=	10058.71
Labor and Maintenance Cost	=	26834.66
Total Operating Cost/Year	=	45954.76
Operating Cost in Cents/1000 Gals	=	1.31

Total Costs in Cents/1000 Gals	=	3.99

Other Data

Exit Temp	=	60.00
Lbs Air/Lbs Water	=	13.67
Pressure Drop (In. Water)	=	.05
Max Entering pH Required	=	10.87

(The optimized values of the design variables are liquid flowrate, 600 lb/hr ft^2; gas flowrate, 1000 lb/hr ft^2; vertical spacing of splash bars, 3 in.; horizontal spacing of splash bars, 2 in.; width of tower, 7 ft. The computer output for these values is presented above.)

APPENDIX

I. DERIVATION OF LIQUID TEMPERATURE PROFILE IN A COUNTERCURRENT TOWER

To determine how humidification due to the air-water contact affects design, it is necessary to know the temperature profile of the liquid in the tower. A preliminary ammonia-stripping-tower design is based on an assured mean temperature, and this results in a tower of known geometry. The problem is to calculate the temperature profile in this tower to see if the assured mean temperature is correct. If not, the ammonia-stripping-tower design is repeated with a new mean temperature.

Performing an enthlapy balance around a differential element of volume for the tower of Figure 13 yields

$$L\, C_p\, dT = G\, di_y \tag{72}$$

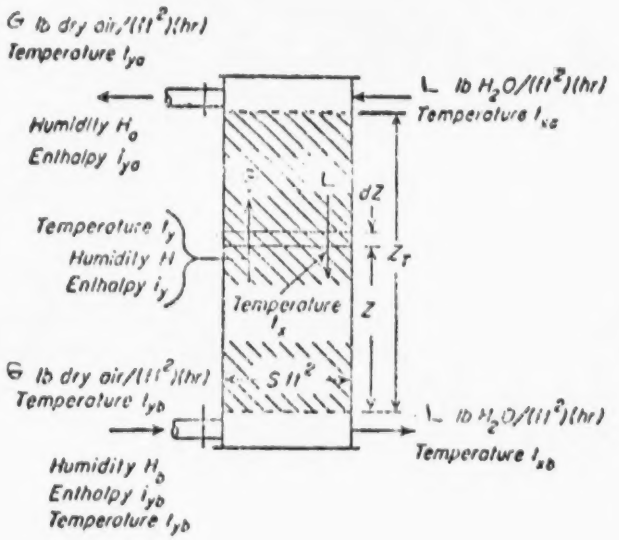


Figure 13[24]

FLOW DIAGRAM OF COUNTERCURRENT WATER COOLER

The rate at which enthalpy is transferred between phases can be written as

$$L\, C_p\, dT = G\, di_y = Ka\left(i_i - i_y\right) dz \qquad (73)$$

where i_y is the enthalpy of the air at a given point in the tower, and i_i is the enthalpy of air in equilibrium with the bulk temperature of the water at that point.

For particle packings,[14,35] the enthalpy transfer coefficient may be estimated by

$$K'a = 9.1\left(G^{.7} L^{.07}\right) \qquad (74a)$$

for film packings[15,16]

$$K'a = 1.38\, G^{.75} \qquad (74b)$$

for splash packings, see Table 18 and Figure 14.

The psychrometric chart in Figure 15 can be described in terms of mathematical equations. We derived the following equations

$$i_i = \exp(1.77 + .025T) \qquad (75a)$$

$$H = 10\left(.015T_{WB} - 2.855\right) - .000229\left(T_{DB} - T_{WB}\right) \qquad (75b)$$

$$C_S = .24 + .46\, H \qquad (75c)$$

$$i_y = C_S T_{DB} + 1092\, H \qquad (75d)$$

where i_i is the enthalpy of a saturated vapor, H humidity, C_S humid heat, T_{WB} wet bulb temperature, T_{DB} dry bulb temperature, and i_y enthalpy of an unsaturated vapor. Enthalpies are referred to 0°F. The boundary conditions for which Equation 73 is to be solved are

Table 18

CORRELATIONS OF ENTHALPY TRANSFER COEFFICIENT AND PRESSURE DROP FOR SPLASH PACKINGS

Values are given in terms of the empirical constants A, B, and n in the equations

$$K'a = \frac{A}{V_S}\left(L^{1-n}\ G^{n}\right)$$

$$\frac{\Delta P}{z} = \left(\frac{B}{V_S}\right)\left(G^2\right)\left(\frac{S_{H,ref}}{S_H}\right)^{*}$$

where V_S (ft) is the vertical spacing according to the deck configurations of Figure 14.

Deck	A	B x 10^8	(VTH) Vertical Thickness of Splash Bar, in.	n	(HTH) Horizontal Thickness of Splash Bar, in.	($S_{H,ref}$) Horizontal Spacing in Fig.14, in.
A	.08	.34	3/8	.62	2	8
B	.07	.34	3/8	.62	2	8
C	.0736	.40	7/8	.60	3/8	1-1/8
D	.0595	.40	7/8	.58	3/8	1-1/8
E	.055	.60	1-1/2	.46	7/8	3-3/4
F	.05	.26	1-7/8	.51	7/8	4
G	.052	.40	1-7/8	.57	7/8	

Table 18 (cont.)

H	.0635	.75	7/8	.47	7/8	4-1/2
I	.0675	.52	1	.57	1/2	2-1/4
J	.0515	.40	7/8	.54	7/8	6

*Note: Kelly and Swenson give this equation as

$$\frac{\Delta P}{N} = BG^2 + C \sqrt{S_F}\, L\, G_E^2$$

where C is a constant, S_F vertical free fall of a drop, N the number of decks, and G_E an equivalent pressure loss air-mass flow. The first term is the contribution of the packing and the second that of the drops. For the small vertical spacing encountered in ammonia stripping (1-4 in.), calculations show that the drops contribute little to the pressure drop so that the second term can be neglected. Also, since the pressure drop and horizontal spacing are approximately linearly related, the factor $S_{H,ref}/S_H$, where $S_{H,ref}$ is the horizontal spacing given in Figure 14. The final equation is obtained when the substitution $N = Z/V_S$ is made.

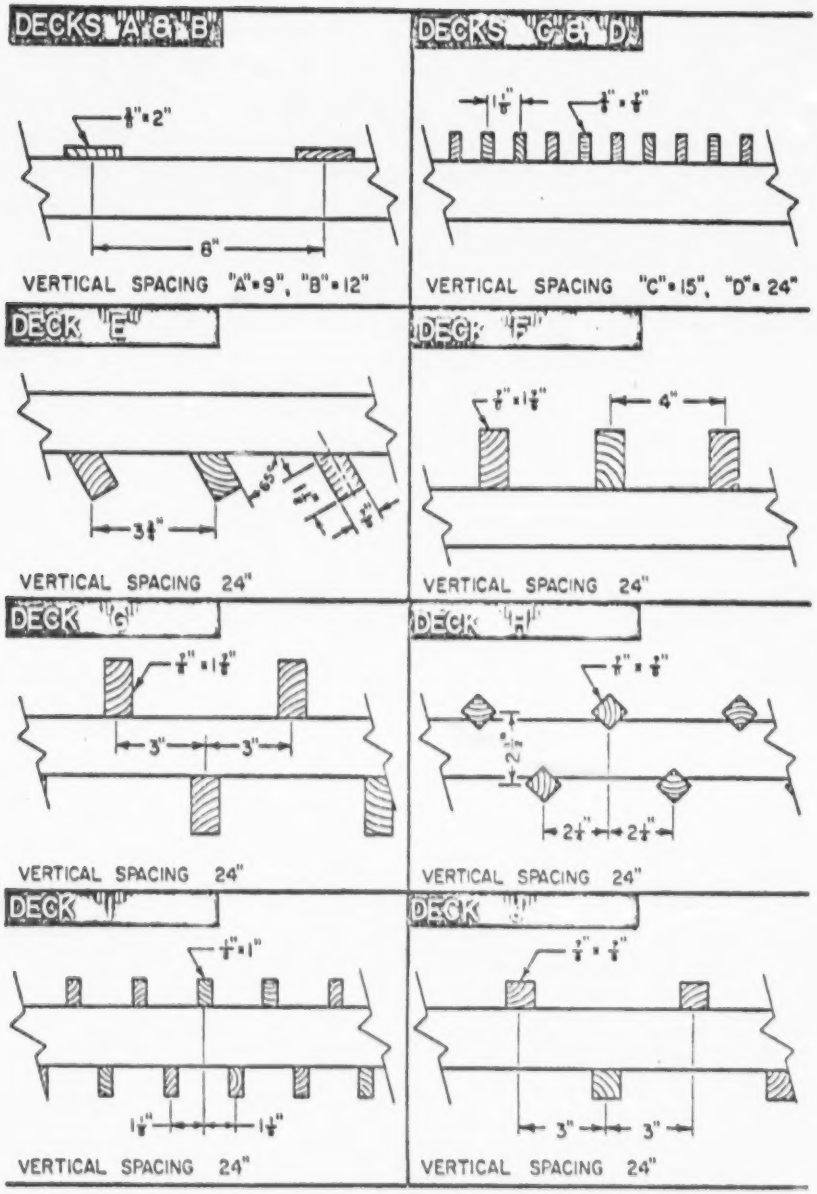


Figure 14[17]

DECK CONFIGURATIONS

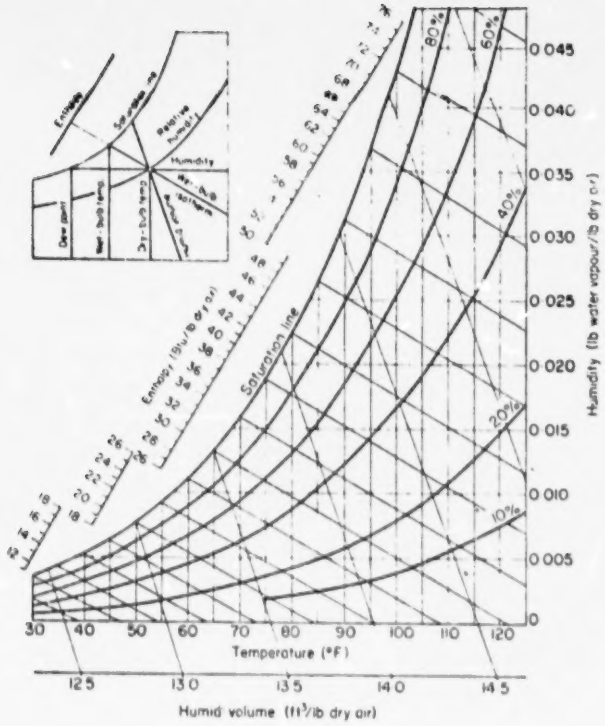


Figure 15[30]

PSYCHROMETRIC CHART

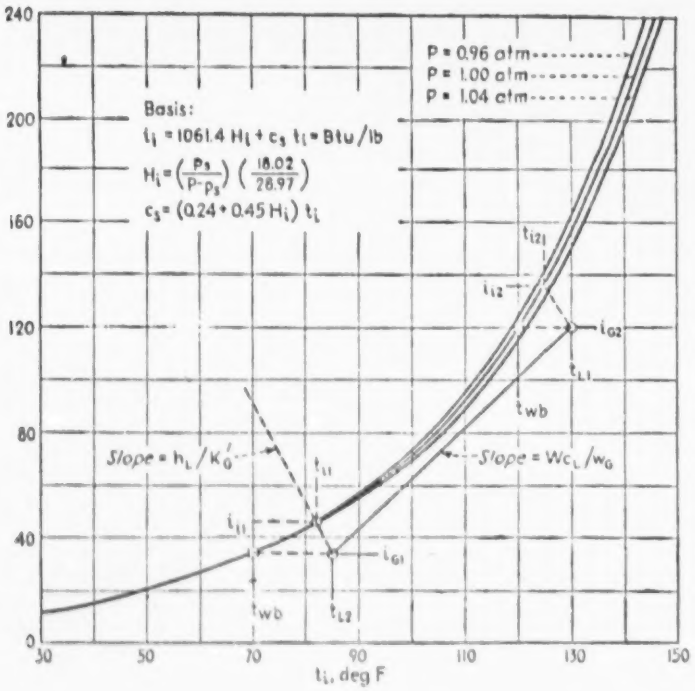


Figure 16[23]

SATURATION ENTHALPY CURVE

$$T = T_E \quad \text{at} \quad Z = h \tag{76a}$$

$$i = i_e \quad \text{at} \quad Z = 0 \tag{76b}$$

where h is the height of the tower, which is known from the ammonia-stripping design calculations.

To solve Equations 73, 76a and 76b rigorously, an involved numerical scheme would be necessary. However, the problem may be simplified by noting that for temperatures below 70°F, the saturation enthalpy curve becomes nearly linear (see Figure 16). Therefore, Equation 75a may be expanded in Taylor series around a reference temperature T_{Ref} and truncated after the linear term.

$$i_i = 5.87\, e^{.025T_{ref}} + .025\, e^{.025T_{ref}} (T - T_{ref}) \tag{77}$$

Integrating Equation 72 from the bottom of the tower to any point within the tower,

$$i_y = \frac{L}{G} (T - T_B) + i_e \tag{78}$$

where T_B is the exiting temperature of the liquid. T_B is a constant but is unknown.

Substituting Equations 81 and 82 into Equation 77,

$$\frac{dT}{dZ} + BT = A$$

where

$$A = \frac{Ka}{L} \left[e^{.025T_{ref}} 5.87 - .147T_{ref} + \frac{L}{G} T_B - i_e \right]$$

$$B = \frac{Ka}{L} \left[-.147e^{.025T_{ref}} + \frac{L}{G} \right]$$

Separating variables and integrating from the top of the tower to any point within the tower,

$$T = \frac{A}{B} + \left(T_E - \frac{A}{B}\right) e^{B(h-z)} \tag{79}$$

Substituting $T = T_B$ at $Z = 0$ into Equation 79 and solving for T_B

$$T_B = \frac{\frac{C}{B}\left(1 - e^{Bh}\right) + T_E\, e^{Bh}}{1 + \frac{Ka}{BG}\left(e^{Bh} - 1\right)} \tag{80}$$

where $C = \frac{Ka}{L}\, e^{.025T_{ref}} \left(5.87 - .147T_{ref}\right) - i_e$

The mean liquid temperature in the tower is

$$T_{mean} = \frac{1}{h} \int_0^h T(Z)\, dZ$$

$$T_{mean} = \frac{A}{B} + \frac{\left(T_E - \frac{A}{B}\right)\left(e^{Bh} - 1\right)}{Bh} \tag{81}$$

To determine the liquid temperature profile, Equation 79 may be evaluated for several values of Z.

The procedure was programmed on the computer and typical output is shown in Tables 19 and 20. From this output it is seen that the temperature drop occurs mainly at the top of the tower and that the mean liquid temperature is very close to the wet bulb temperature of the entering air. Thus, the analysis of the ammonia stripping tower can be based upon isothermal design principles using the entering wet bulb temperature of the air as the design temperature for a first approximation. Then, the temperature profile and mean temperature can be calculated, and the first approximation checked. If the wet bulb temperature and mean temperature differ significantly, the design procedure is repeated using the mean temperature.

Table 19

LIQUID TEMPERATURE PROFILE FOR A PARTICLE PACKED TOWER
(Tower design: height, 15 ft; G, 450 lb/hr ft^2;
L, 125 lb/hr ft^2; feed temperature, 70°F;
wet bulb temperature, 60°F; dry bulb temperature, 95°F)

Height as Measured from Bottom of Tower, ft	Liquid Temperature, °F
0.0	60.29
.75	60.29
1.50	60.29
2.25	60.29
3.00	60.29
3.75	60.29
4.50	60.29
5.25	60.29
6.00	60.29
6.75	60.29
7.50	60.29
8.25	60.29
9.00	60.29
9.75	60.29
10.5	60.29
11.25	60.29
12.00	60.29
12.75	60.29
13.50	60.34
14.25	61.02
15.00	70.00
	60.47[a]

[a]Mean.

Table 20

LIQUID TEMPERATURE PROFILE FOR A FILM GRID PACKED TOWER
(Tower design: height, 15 ft; G, 2000 lb/hr ft^2;
L, 600 lb/hr ft^2; feed temperature, 70°F;
wet bulb temperature, 60°F; dry bulb temperature, 95°F)

Height as Measured from Bottom of Tower, ft	Liquid Temperature, °F
0.00	60.34
.75	60.37
1.50	60.40
2.25	60.44
3.00	60.49
3.75	60.55
4.50	60.63
5.25	60.73
6.00	60.86
6.75	61.02
7.50	61.22
8.25	61.47
9.00	61.79
9.75	62.19
10.50	62.69
11.25	63.33
12.00	64.13
12.75	65.13
13.50	66.40
14.25	67.99
15.00	70.00
	62.34[a]

[a]Mean.

II. ABSORPTION OF CO_2

The rate of absorption of CO_2 into water at pH 7 has been found to be negligibly show. However, the rate into strong alkaline solutions is fast. The amount of CO_2 present in the air used to strip ammonia from wastewater is potentially capable of neutralizing all of the lime alkalinity before the ammonia is removed. The question is whether the rate of CO_2 absorption is appreciable at the typical operating pH of an ammonia stripping tower.

The reactions that take place in solution are[2]

$$CO_2 + OH^- \longrightarrow H\,CO_3^{-1} \qquad \text{(R2)}$$

$$H\,CO_3^{-1} + OH \longrightarrow CO_3^{-2} + H_2O \qquad \text{(R3)}$$

Reaction R3 can be considered to be instantaneous while Reaction 2 proceeds at a finite rate. Thus, the two reactions may be combined to give the overall reaction

$$CO_2 + 2OH^- \longrightarrow CO_3^{-2} + H_2O \qquad \text{(R4)}$$

Reaction 4 shows that as a result of CO_2 absorption, the pH will decrease and carbonate may precipitate as $CaCO_3$.

From the work done by Hitchcock[13] on CO_2 absorption into alkaline solutions, the ratio of the absorption rates for a solution of some given normality N_1 to that of another N_2 can be expressed approximately as

$$\frac{.06 + N_1}{.06 + N_1} = \frac{\text{Rate for Solution 1}}{\text{Rate for Solution 2}} \qquad (82)$$

The liquid-phase mass-transfer coefficient for CO_2 absorption into water (pH = 7) for particle packings has been found to be[21]

$$K_L a = .015\,L^{.96} \qquad (83)$$

Thus, the mass transfer coefficient for an alkaline solution can be expressed as

$$K_L a(\text{alkaline}) = .015 \left(\frac{.06 + N}{.06}\right)_L^{.96} \qquad (84)$$

For the extreme case of an operating pH of 12, the mass-transfer coefficient for an alkaline solution is 1.3 greater than that for water, while for the more typical operating pH of 11 the ratio is only 1.02. Since experimental data[13] indicate that the rate of CO_2 absorption into water is much less than that of ammonia, we can also neglect this effect at the range of pH under consideration.

This conclusion can also be demonstrated from mass transfer theory using Colburn's equation for dilute solutions[26]

$$\frac{K_L aPZ}{HG_M} = \ln \frac{Y_{enter}}{Y_{exit}} \qquad (85)$$

where Y is the mole fraction of CO_2 in the gas stream, H is Henry's constant.

Rearranging Equation 85

$$Y_{exit} = Y_{enter} \exp\left[-\frac{K_L aPZ}{HG_M}\right]$$

and substituting in the following values

$$G = 600 \text{ lb/ft hr}$$

$$K_L a = 2 \text{ lb mole/hr ft}^2(\text{lb mole/ft}^3)$$

$$H = \frac{412 \text{ atm}}{\text{lb mole/ft}^3}$$

$$P = 1 \text{ atm}$$

$$Z = 7 \text{ ft}$$

$$Y_{enter} = 2.2 \times 10^{-4}$$

we obtain the value

$$Y_{exit} = 2.2 \times 10^{-4} \exp\left[-\frac{2(1)(7)}{412(600/29)}\right]$$

$$\approx 2.2 \times 10^{-4}$$

For completeness for the computer program, Reaction 4 has been combined with the pH drop equation (from Section II) to estimate the slight drop in pH across the tower due to CO_2 absorption.

III. PENETRATION THEORY

A. Gas-Phase Analysis

A liquid drop falls through a gas flowing upwards which absorbs the solute in the drop. A particle of the gas initially at the bottom of the drop is in contact with the liquid for the time θ required for the gas particle to travel across the surface of the drop. This contact time is equal to the diameter of the drop divided by the relative velocity between the gas and liquid. During the time θ, during which the gas particle is subject to unsteady state diffusion of solute, the governing equation is[35]

$$\frac{\partial C_G}{\partial \theta} = \mathcal{D}_{SG}\left(\frac{\partial^2 C_G}{\partial Z^2}\right) \tag{86}$$

where C_G is the concentration of the gas, $\mathcal{D}_{SG}$ is the diffusivity, θ is time, Z is depth of penetration of solute.

For short contact times, the molecules of the solute are never able to reach the depth corresponding to the thickness of the particle, so that from the solute's point of view this depth

is infinite. Thus the boundary conditions are

$$C_G = C_{OG} \quad \text{at} \quad \theta = 0, \text{ for all } Z$$

$$C_G = C_i \quad \text{at} \quad Z = 0, \ \theta > 0$$

$$C_G = C_{OG} \quad \text{at} \quad Z = \infty, \text{ for all } \theta$$

The solution of Equation 86 is[35]

$$C_G = C_{OG} + C_i - C_{OG} \left(1 - \frac{2}{\pi} \int_0^{Z/2\left(\theta \mathcal{D}_{SG}\right)^{.5}} e^{-\eta^2} d\eta \right) \tag{87}$$

The flux at the surface is

$$N_S = \mathcal{D}_{SG} \left(\frac{\partial C_G}{\partial Z} \right)_{Z=0} = \left(C_i - C_{OG} \right) \sqrt{\frac{\mathcal{D}_{SG}}{\pi\theta}}$$

$$N_{S,ave} = \frac{1}{\theta} \int_0^{\theta_C} \left(C_i - C_{OG} \right) \sqrt{\frac{\mathcal{D}_{SG}}{\pi\theta}} \, d\theta$$

$$N_{S,ave} = 2\left(C_i - C_{OG} \right) \sqrt{\frac{\mathcal{D}_{SG}}{\pi\theta_C}} \tag{88}$$

where $N_{S,ave}$ is mean molar flux, lb mole/ft^2 hr.

To use a partial-pressure driving force, we note from the ideal gas law that

$$C = \frac{P}{RT} \tag{89}$$

Thus

$$N_{S,ave} = \frac{2}{RT}\left(P_i - P_{OG}\right)\sqrt{\frac{\mathcal{D}_{SG}}{\pi\theta_C}} \qquad (90)$$

The gas film coefficient K_G (lb mole/ft^2 hr atm) is defined as

$$K_G = \frac{N_A}{P_A - P_i}$$

Thus

$$K_G = \frac{2}{RT}\sqrt{\frac{\mathcal{D}_{SG}}{\pi\theta_C}} \qquad (91)$$

If u is the relative velocity between gas and liquid, and D the diameter of the drop, then

$$\theta_C = \frac{D}{u}$$

and for laminar flow

$$K_G = \frac{2}{RT}\sqrt{\frac{\mathcal{D}_{SG}u}{\pi D}} \qquad (92)$$

For turbulent flow, assuming a normal distribution for θ_C

$$\theta_C \cong \left(\frac{1}{2}\right)\left(\frac{D}{u}\right)$$

then

$$K_G = \frac{2}{RT}\sqrt{\frac{2\mathcal{D}_{SG}u}{\pi D}} \qquad (93)$$

B. Liquid-Phase Analysis

The governing equation for transfer of solute in the liquid phase is similar to that for the gas phase[35]

$$\frac{\partial C_L}{\partial \theta} = \mathcal{A}_{SL} \left(\frac{\partial^2 C_L}{\partial Z^2} \right) \tag{94}$$

where C_L is the liquid concentration and

$$C_L = C_{OL} \quad \text{at} \quad \theta = 0, \text{ for all } Z$$

$$C_L = C_i \quad \text{at} \quad Z = 0, \ \theta > 0$$

$$C_L = C_{OL} \quad \text{at} \quad Z = \infty, \text{ for all } \theta$$

As before

$$N_{S,ave} = 2 \left(C_i - C_{OG} \right) \sqrt{\frac{\mathcal{A}_{SL}}{\pi \theta_C}} \tag{95}$$

But now the contact time is equal to the time it takes the drop to fall from one splash bar to the next. The vertical spacing is denoted S_V. Thus

$$\theta_C = \frac{S_V}{u_{drop}} \tag{96}$$

where u_{drop} is the absolute velocity of the drop.

Defining the liquid film coefficient as

$$K_L = \frac{N_A}{C_i - C_A}$$

one obtains

$$K_L = 2\sqrt{\frac{\Delta_{SL} u_{drop}}{\pi S_V}} \tag{97}$$

These gas and liquid transfer coefficients can be combined to give an overall gas or liquid-film coefficient[26]

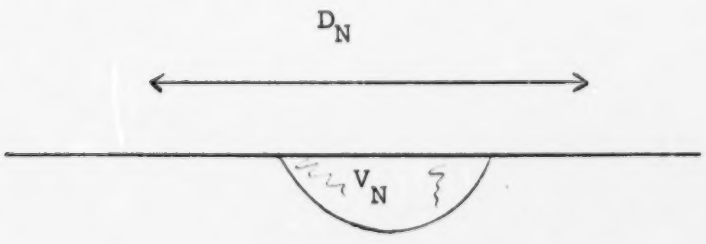
$$K_G = \frac{K_G K_L}{mK_G + K_L} \tag{98a}$$

$$K_L = \frac{mK_G K_L}{mK_C + K_L} \tag{98b}$$

C. Determination of Drop Size for Splash Packing

To apply the above equations, the drop size must be known. It is assumed that buoyancy and surface tension are the major forces and that kinetic and drag effects can be neglected.

Just before a drop detaches itself from the bottom of a slat, it appears as shown below where V_N is the volume of the hemisphere and D_N its diameter.



The buoyancy force is

$$F_B = V_N g\Delta\rho = V_N g\rho_W$$

The interfacial tension force is

$$F_S = \pi\sigma D_N$$

where σ is the surface-tension force.
Equating these forces

$$V_N = \frac{\pi\sigma D_N}{g\ \rho_W}$$

But

$$V_{drop} = FV_N$$

where F is the fraction of the drop which detaches. Thus,

$$V_{drop} = \frac{F\pi\sigma D_N}{\rho_W g} \tag{99}$$

From $V_{drop} = F\ V_N$ we obtain

$$\frac{4}{3}\pi\left(\frac{D_{drop}}{2}\right)^3 = \frac{F}{2}\left[\frac{4}{3}\pi\left(\frac{D_N}{2}\right)^3\right]$$

$$D_{drop} = \left(\frac{F}{2}\right)^{1/3} D_N \tag{100}$$

Substituting 99 into 100

$$D_{drop} = \frac{F}{2}^{1/3} \left(\frac{g\rho_W V_{drop}}{F \pi \sigma} \right)$$

$$= \frac{F}{2}^{1/3} \left[\frac{g \rho_W \pi}{F \pi \sigma} \left(\frac{D^3_{drop}}{6} \right) \right]$$

$$= \frac{\rho_W g D^3_{drop}}{2^{1/3} F^{2/3} \sigma \cdot 6}$$

$$D_{drop} = \sqrt{\frac{7.56 \sigma F^{2/3}}{\rho_W g}} \qquad (101)$$

F is a function of $D_N/2V_{drop}^{1/3}$ which can be written as[11]

$$\frac{D_N}{2V_{drop}^{1/3}} = \left(\frac{2}{F}\right)^{1/3} \left[\frac{D_{drop}}{2 \pi/6 D^3_{drop}^{1/3}} \right]$$

$$= \frac{1}{2} \left(\frac{2}{F}\right)^{1/3} \left(\frac{6}{\pi}\right)^{1/3}$$

$$= \frac{1}{2} \left(\frac{12}{\pi F}\right)^{1/3}$$

and

$$F = \psi\left(\frac{D_N}{2V_{drop}^{1/3}}\right) = \psi\left[.5\left(\frac{12}{\pi F}\right)\right]^{1/3}$$

$$= \psi\left[.5\left(\frac{3.82}{F}\right)^{1/3}\right]$$

$$F = \psi\left[\frac{.78}{F^{1/3}}\right] \qquad (102)$$

Table 21 gives the empirical function ψ as determined by Harkins and Brown[10]. Solving Equation 102 by trial and error in conjunction with Table 21 yields F = .60.

Substituting the following values in Equation 101

$F = .60$

$\sigma = 73$ dynes/cm

$g = 980$ cm/sec^2

$\rho_W = 1$ g/cm^3

gives

$D_{drop} = 6.32$ mm

This drop size agrees with visual observations of 5 to 6 mm in cooling towers.

Table 21[10]

SURFACE-TENSION CORRECTION FUNCTION

$D_N/2V_{Drop}^{1/3}$	$\Psi(D_N/2V_{Drop}^{1/3})$
0.00	(1.0000)
0.30	0.7256
0.35	0.7011
0.40	0.6828
0.45	0.6669
0.50	0.6515
0.55	0.6362
0.60	0.6250
0.65	0.6171
0.70	0.6093
0.75	0.6032
0.80	0.6000
0.85	0.5992
0.90	0.5998
0.95	0.6034
1.00	0.6098
1.05	0.6179
1.10	0.6280
1.15	0.6407
1.20	0.6535
1.225	0.6555
1.25	0.6521
1.30	0.6401
1.35	0.6230
1.40	0.6033
1.45	0.5847
1.50	0.5673
1.55	0.5511
1.60	0.5352

D. Determination of Contact Time for Splash Packing

The distance an object falls in a given time starting from rest is given by

$$S = 1/2\ g\ t^2,\ ft$$

$$t = \sqrt{2S/g}$$

$$t = \sqrt{S/16}$$

$$t = \sqrt{\frac{S}{4}} \qquad (103)$$

where S is in feet, t in seconds, and g is the gravitational constant in ft/sec^2.

$$u_{final} = \sqrt{2gS} = \sqrt{64S} = 8\sqrt{S}\ \ ft/sec$$

$$u_{ave} = \frac{u_f - 0}{2} = 4\sqrt{S} \qquad (104)$$

E. Determination of Surface Area for Transfer per Unit Volume

Let L be the liquid rate per unit cross-sectional area, u_{drop} the velocity of a drop, and m its mass.

In unit time a drop will fall a distance u, and a liquid mass L' will flow through a unit cross-sectional area.

Let n be the number of drops per unit volume. Then

$$(n)(m)(u)(1) = L$$

$$n = L/m\ u$$

$$m = \rho_W V_{drop} = \rho_W \frac{\pi}{6} D^3_{drop}$$

$$a = n\left(S_{drop}\right) = n\left(4 \pi r^2\right) = n \pi D^2_{drop}$$

$$n = a/\pi D^2_{drop}$$

$$\frac{a}{\pi D^2} = \frac{L}{\rho_W \frac{\pi}{6} D^3}$$

$$a = \frac{6 L}{\rho_W u_{drop} D_{drop}} \qquad (105)$$

IV. SOLUTION OF THE GOVERNING SYSTEM OF EQUATIONS FOR A CROSS-FLOW TOWER

The derivation of the design equation for a cross-flow stripping tower where the design temperature is the wet bulb temperature of the entering air is as follows.

Define the dimensionless variables

$$U = K_G a \, m \, C_L$$

$$W = K_G a \, C_G$$

$$\zeta = \frac{K_G a \, m}{L_M} z$$

$$\eta = \frac{K_G a}{G_M} x$$

Making these changes of variables, Equations and become

$$-\frac{\partial U}{\partial \xi} = U - W = \frac{\partial W}{\partial \eta} \tag{106a}$$

with the boundary conditions

$$U(\eta,0) = U_0 \tag{106b}$$

$$W(0,\xi) = 0 \tag{106c}$$

where

$$U_0 = K_G a\, m\, C_{OL}$$

From the papers of Schechter and Kang[32] and Vouyoucalos[37], it may be deduced that the change in liquid concentration across the width of the tower is small in comparison to that across its height. This suggests seeking a solution of the form

$$U(\eta,\xi) = U_{mean}(\xi) + \sum_{i=1}^{\infty} \eta^i\, U_i(\xi)$$

As a first approximation, the series is truncated after the first term. This approximation will be checked later, and if it proves to be inadequate, a higher-order approximation will be made. If

$$U(\eta,\xi) \sim U_{mean}(\xi)$$

Equation 106 becomes

$$-\frac{d\, U_{mean}}{d\xi} = U_{mean} - W = \frac{\partial W}{\partial \eta} \tag{107}$$

For a given ζ, Equation 107 becomes

$$\frac{dW}{d\eta} = U_{mean} - W$$

whose solution is

$$W = U_{mean} (1 - e^{-\eta}) \tag{108}$$

Integrating Equation 106 with respect to η from $\eta = 0$ to $\eta = \eta_0$, where

$$\eta_0 = \frac{K_G a}{G_M} x_0$$

is the dimensionless width of the tower, gives

$$- \frac{dU_{mean}}{d\zeta} = \frac{W_0}{\eta_0}$$

where W_0 is given by Equation 108 whose solution, when evaluated at $\eta = \eta_0$, is

$$U(\zeta) = U_0 \exp -\left[\frac{\zeta}{\eta_0} \left(1 - e^{-\eta_0}\right)\right] \tag{109}$$

where

$$U_0 = K_G a \; m \; C_{OL}$$

Substituting back the original variables and solving for z yields

$$z = \frac{L_M}{mG_M} \left[\frac{x_o}{1 - \exp\left(-\frac{K_G a}{G_M}\right) x_o}\right] \ln \frac{C_{OL}}{C_{L,mean}} \tag{110}$$

Equation 110 may be used to calculate either the height or width of the tower once the other has been set.

A check may be made on Equation 109. For heat exchangers, Binnie and Poole[5] were able to obtain an exact solution of Equation 106 in the form of a series. They gave an example problem in which water entered at 40°F and a liquid at 100°F, and the dimensions of the heat exchanger were 13.76 by 20 ft. They found the exit temperature of the liquid was 52.84°F while Equation 109 gave 54.15°F. This indicates that the first approximation is sufficient and that a higher-order approximation is not necessary.

V. RESTRICTIONS ON LIQUID AND GAS FLOWRATES FOR GRID AND SPLASH PACKING

The minimum liquid wetting rate (MWR) vs the spacing or pitch of grid packing is given below. If the optimum liquid rate is below this value, the liquid flowrate should be increased to this value, and a new calculation made omitting the optimization procedure. It should be noted that Johnstone and Singh's correlations are valid for liquid flowrates above 480 lb/hr ft^2. Thus, as a precautionary measure, the liquid flowrate should be above this value. Also, to prevent excessive spraying, gas rates above 3000 lb/hr ft^2 should be avoided. Although there is not similar information on splash packing, these rules should also be used for splash packing since at close spacing splash packing resembles grid packing.

If the user wishes to operate at a liquid flow rate less than MWR, he may estimate the fraction of the packing wetted, F_W, by the table given below. To convey this information to the computer program, he should read in the product of VO and F_W in place of VO.

Table 22

MWR AND RECOMMENDED MINIMUM LIQUID FLOW RATE VS PITCH FOR GRID PACKING

Pitch, in.	MWR, lb/hr ft^2	Recommended Minimum Liquid Flowrate, lb/hr ft^2
.625	675	675
1.00	600	600
1.25	525	525
1.50	450	480
1.75	375	480
2.00	300	480
2.25	225	480

Table 23

FRACTION OF GRID PACKING WETTED VS LIQUID RATE AS FRACTION OF MWR

LP/MWR	F_W
1.0	1.00
.9	.875
.8	.750
.7	.625
.6	.500
.5	.375
.4	.250
.3	.125
.2	0.0

```
C001              REAL K4,K5,L, LP, NUM, K6, NH3CT,MULR,MUGR,N
C002              COMMON        TCNH3 , NH3CT , L ,
                 .       LP , RHOL , RHOLR , GP , AP , NUM , SCLR , MULR ,
                 .       EO , SCGR , MUGR , REYR , ALPHL , BETAL , RHOGR ,
                 .       ALPHA , N , BETA , GAMA , C , P , K4 , BETAP , RHOG , T ,
                 .      TWB,TDB, CPA, PHI, K5, K6, AC, DGR, CLR, TE, JT,
                 .     SMATX(3,2), DMATX(16,2), IN, IO,OPT
C003              COMMON SHELL,FAN,PUMP,FANPW,XLM,DETPG,TR,PUMPW,PACK,STRUC,CAP,OP,
                 .  OPPG,ACPG
C004           92 FORMAT (6F15.3)
C005           91 FORMAT (6F10.3)
C006           93 FORMAT(3F10.3)
0007              IN=5
C008              IO=6
C009              READ(IN,93) LP,GP,OPT
C010              READ (IN,91)((SMATX(I,J),J=1, 2), I=1, 3)
0011              READ  (IN,91)  ((DMATX(I,J),J=1, 2), I=1,16)
C012              WRITE(IO,92) SMATX,DMATX
C013              IF(OPT) 10,20,10
0014           10    LP=200.
0015           20 L=SMATX(1,1)*347000.
                C
                C                  TE, ENTERING LIQUID TEMP.
                C                  T, DESIGN TEMP. (MEAN TEMP.)
                C
0016                 TE=SMATX(3,1)
C017                 NUM=DMATX(9,1)                                    AMON2065
C018                 AP=DMATX(1,1)                                     AMON2070
C019                 EO=DMATX(2,1)                                     AMON2075
C020                 BETAL=DMATX(3,1)                                  AMON2080
C021                 ALPHL=DMATX(4,1)
0022                 TCNH3=SMATX(2,1)
C023                 NH3CT=SMATX(1,2)
C024                 TDB=DMATX(10,1)                                   AMON2100
C025                 TWB=DMATX(11,1)                                   AMON2105
0026                 CPA=DMATX(6,1)                                    AMON2110
C027                  T=TWB
C028                 JT=1
0029                 CALL OPTAP
C030               CALL  STRAP
0031              STOP
0032                 END                                               AMON  60
```

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FORTRAN IV G LEVEL 1, MOD 3            STRAP            DATE = 69245        09/34/50            PAGE 0001

0001                SUBROUTINE STRAP
0002                REAL K4,K5,L, LP, NUM, K6, NH3OT,MULR,MUGR,N,
                   .   KWKB, KB, KGA, MOL, MINPH, KLA, MPHGR
0003                INTEGER TYPE
0004                COMMON          TGNH3 , NH3OT , L ,
                   .       LP , RHOL , RHOLR , GP , AP , NUM , SCLR , MULR ,          AMON   3
                   .       EC , SCGR , MUGR , HENR , ALPHL , BETAL , RHOGR ,
                   .       ALPHA , N , BETA , GAMA , C , P , K4 , BETAP , RHOG , T ,  AMON   6
                   .      TWP,TCG, CPA, PHI, K5, K6, AL, DGR, DLR, TE, JT,
                   .     SMATX(3,2), CMATX(16,2), IN, IO,CPI
0005                COMMON SHELL,FAN,PUMP,FANPW,XLM,GETPG,TP,PUMPW,PACK,STRUC,CAP,CP,
                   .  CPPG,ACPG
                  C  PACK
0006                3040    AREA=L/LP                                              AMON2175
0007                        MUW=2.42                                               AMON2185
0008                        TYPE=CMATX(12,1)                                       AMON2190
0009                        GF=3600.*SQRT(32.2*EC**3*RHOL*RHOG*RHOLR*RHOGR/(AP*MULR**
                   .     .2)*EXP(-4.*(LP/GP)**.25*(RHOG*RHOGR/(RHOL*RHOLR))**.125))
0010                IF(TYPE-1) 20,20,10
0011              10 GF=10.*GF
0012              20 IF(GP-GF) 40,30,30
0013              30 GP=.6*GF
0014              40    Z=(GAMA*LP**N*BETA*LP**C*GP**P)/(1.-K4*LP/GP)*ALOG(K5*LP/GP+K6)AMON2215
0015                    S=CMATX(5,1)                                               AMON2220
0016                    DLTAP=ALPHA*10.**(BETAP*LP)*GP**S/(RHOG*RHOGR)*Z
0017                    FRACT=(TGNH3-NH3OT)/TGNH3
0018                    KWKB=5.56E-10*EXP(-3862.9/(.5555*T+255.2)+1.3)             AMON2235
0019                    HCONC=(1.-FRACT)/FRACT*KWKB
0020                  MINPH=ALOG(1./HCONC)/2.3025E509
0021                    KLA=.015*L**.96*(.06+MCONC)/.06                            AMON2385
0022                    HNCO2=.72E*10.**(.00135*(.5555*T-32.))/56.5
0023                    KGA=KLA/HNCO2
0024                    CO2R=EXP(-KGA*Z/GP)                                        AMON2400
0025                    CO2RS=.9E*3.3E-04*(1.-CO2R)/44.
0026                    COCO2=CO2RS/LP*RHOL*RHOLR*.03531
0027                    OHORP=(TGNH3-NH3OT)*(1.-FRACT)/17.E03
0028                    KB=1.8E-05*EXP(-6348.5/(.5555*T+255.2)+21.3)               AMON2420
0029                    CONHT=KB*KWKB/HCONC
0030                    MPHGR=ALOG((CONHT/(CONHT-2.*COCO2-OHORP))/2.30258509
0031                  WRITE(IO,1005)
0032              1005 FORMAT(1H1,'AMMONIA STRIPPING FOR WASTE WATER TREATMENT-COUNTERCUR
                   .RENT TOWER')
0033                    WRITE(IO,8000)
0034              8000 FORMAT(1H0,'CAPITAL COSTS($)'    )
0035                    WRITE(IO,8003)
0036              8003 FORMAT(120H0          PACKING COST      COST OF FAN          COST O
                   .F PUMP       STRUCTURE COST       TOTAL CAPITAL C ST           )
0037                  WRITE(IO,801) PACK,FAN,PUMP,STRUC,CAP
```


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```
C0038          801   FORMAT(5F20.2)
C0039               WRITE(IO,8002)
C04C          8002 FORMAT(1HO,'OPERATING COSTS(1/YR.)'  )
C041                WRITE(IC,8004)
0042          8004 FORMAT(120HO      PUMPING POWER COST  FAN POWER COST  CHEM,LABOR,+
                   .MAIN COST    TOTAL OPERATING COST                              )
C043                WRITE(IO,801) PUMPW, FANPW,XLM,OP
0044               WRITE(IC,700)
C045           700 FORMAT(1HO,'COSTS IN CENTS PER 1000 GAL.'  )
C046          8005 FORMAT(120HO            OPERATING COST      DEBT SERVICE         TOT
                   .AL COST                                                        )
C047               WRITE(IC,8005)
C048               WRITE(IC,801) OPPG,DETPG,ACPG
C049               WRITE(IC,9000)
0050          9000 FORMAT(1HO,'DIMENSIONS OF TOWER AND OPERATING CONDITIONS'   )
C051           901          FORMAT(6F20.2)
C052                WRITE(IC,9001)
0053          9001 FORMAT(1HO,'                TYPE          MEAN TEMP(F)            ',
                   1'ENTERING CONC(MG/L)   EXIT CONC(MG/L)                          2)
C054                WRITE(IO,901) DMATX(12,1),T,TCNH3,NH3CT
C055                WRITE(IC,9003)
0056          9003 FORMAT(1HO,'    THROUPUT(MILLION GAL/DAY)      TE(F)              ',
                   .' TWB(F)                TOB(F)              TO(F)  ')
C057               WRITE(IC,901) SMATX(1,1),TE,TWB,TOB,TO
0058                WRITE(IC,9004)
0059          9004 FORMAT(50HO         LP (LB/SQ FT HR)    GP (LB/SQ FT HR)          )
C06C                WRITE(IO,701) LP, GP
C061                WRITE(IC,9005)
C062          9005 FORMAT(120HO              HEIGHT(FT)       AREA(SQ FT)      PRESSURE
                   .DROP (IN. WATER)                                               )
C063               WRITE(IC,901) Z,AREA,DLTAP
C064               IF(TYPE-2.) 550,560,570
C065           550 WRITE(IC,365)
C066           365 FORMAT(1HO,'            REQUIRED PH    ' )
0067               WRITE(IC,901) MINPH
C068               WRITE(IC,9007)
C069               WRITE(IC,9008)
C070               WRITE(IC,905) DMATX(2,2),DMATX(3,2),DMATX(8,1),
                   .DMATX(7,1),DMATX(1,2)
C071               WRITE(IC,378)
C072           378 FORMAT(50HO             CPS($/CU FT)          TIME(HR)         )
0073               WRITE(IC,905) DMATX(6,1),DMATX(4,2)
C074               GO TO 580
C075           560 WRITE(IC,300)
C076           300 FORMAT(1HO,'           REQUIRED PH          GRID HT(IN)          ',
                   .'SPACING(IN)        THICKNESS(IN)    ')
C077               WRITE(IC,901) MINPH,DMATX(2,1),DMATX(3,1),DMATX(4,1)
0C78               WRITE(IC,9007)
```

```
0079            WRITE(IC,9008)
0080            WRITE(IC,905) DMATX(2,2),DMATX(3,2),DMATX(8,1),
               .DMATX(7,1),DMATX(1,2)
0081            WRITE(IC,345)
0082          345 FORMAT(120HO            CPS($/CU FT)          TIME(HR)
               .  VC                  ALPHA                                )
0083            WRITE(IC,905) DMATX(6,1),DMATX(4,2),DMATX( 1,1),DMATX(4,1)
0084            GO TO 580
0085          570     WRITE(IC,9006)
0086         9006 FORMAT(120HO          REQUIRED PH              HTH(IN)
               .VTH(IN)              SF(IN)              VS(IN)              )
0087            WRITE(IC,901) MINPH,DMATX(13,1),DMATX(9,1),DMATX(16,1),DMATX(1,1)
0088            WRITE(IO,9007)
0089         9007 FORMAT(1HO,'OTHER INFORMATION')
0090            WRITE(IC,9008)
0091         9008 FORMAT(120HO              AMF1                AMF2
               .EF                    EP                CE(C/KWH)           )
0092            WRITE(IC,905) DMATX(2,2),DMATX(3,2),DMATX(5,1),
               .DMATX(7,1),DMATX(1,2)
0093          905 FORMAT(5E20.3)
0094            WRITE(IC,9009)
0095         9009 FORMAT(120HO            CPS($/CU FT)          TIME(HR)
               .  VC                  ALPHA              SHREF(IN)           )
0096            WRITE(IC,905) DMATX(6,1),DMATX(4,2),DMATX(14,1),DMATX(4,1),
               .DMATX(15,1)
0097          580 CONTINUE
0098            RETURN
0099            END
```

```
CCC1              SUBROUTINE OPTAM
CC02              REAL K4,K5,L, LP, NUP, K6, NH3CT,MULR,MUGR,N,
                 .     K7,K9,K10,K11,K13,LPF,J,JL,JLL,M,ML,MLL,K12,MLBC,MLLP          AMON   8
CCC3              INTEGER TYPE
CCC4              COMMON         TONH3 , NH3CT , L ,
                 .       LP , PHOL , RHOLR , GP , AP , NUP , SCLR , MULR ,          AMON   3
                 .       EC , SCGR , MUGR , HENR , ALPHL , BETAL , RHOGR ,
                 .       ALPHA , N , BETA , GAMA , C , P , K4 , BETAP , RHOG , T ,  AMON   6
                 .      TWB,TDB, CPA, PHI, K5, K6, AC, DGR, DLP, TE, JT,
                 .     SMATX(3,2), DMATX(16,2), IN, IO,CPT
CCC5              COMMON SHELL,FAN,PUMP,FANPW,XLM,DELPG,TB,PUMPW,PACK,STRUC,CAP,OP,
                 .  CPPG,ACPG
0006           11     DGR=((T+460.)/492.)**1.5
CCC7              MULR=79.5/(T+10.)
CCC8                 DLR=(T+460.)/(MULR*528.)                                      AMON2125
0009                  RHOGR=492./(T+460.)
CC10                 RHOLR=((212.-T)/144.)**.33                                    AMON2135
CC11                 MUGR=((T+460.)/492.)**.5                                      AMON2140
0012                 HENR=10.**(.01233*T-.95)                                      AMON2145
CC13                 SCGR=MUGR/(RHOGR*DGR)                                         AMON2150
CC14                 SCLR=MULR/(RHOLR*DLR)                                         AMON2155
CC15                 RHOL=62.3                                                     AMON2160
0016                  RHOG=.0808
CC17                 K4=1.83/HENR                                                  AMON  15
CC18                 TYPE=DMATX(12,1)                                              AMON  16
0019                 K5=K4*(1.-TONH3/NH3CT)
CC20                 K6=TONH3/NH3CT
CC21                 K10=.0048*L**.9*.54
CC22                 THETA=DMATX(4,2)                                              AMON  20
0023                 EP=DMATX(7,1)                                                 AMON  21
CC24                 K11=3.75E-7*L/EP*THETA                                        AMON  22
0025                 EF=DMATX(8,1)                                                 AMON  23
CC26                 AMF1=DMATX(2,2)                                               AMON  24
CC27                 AMF2=DMATX(3,2)                                               AMON  25
CC28                 PCP=AMF1                                                      AMON  26
0029              IF(TYPE-1) 110,100,110
CC30           100 PCP=1.05*AMF1
CC31           110    PCF=1.5*AMF2                                                AMON  28
0032                 CE=DMATX(1,2)                                                 AMON  29
CC33                 S=DMATX(5,1)                                                  AMON  30
CC34                 K9=14300.*(L/3.47E06)**.6                                     AMON  31
CC35                 PCPU=1.4*AMF2                                                 AMON  32
0036                  K13=(23.25+4.64/AMF2)*L
CC37              IF(TYPE-1) 130,120,130
CC38           120 K13=(18.60+4.64/AMF2)*L
0039           130    PCS=AMF2                                                    AMON  35
CC40                 PHI=1                                                         AMON  36
CC41                 K7=0                                                          AMON  37
```

```
C042                  BETAP=0                                                  AMON  38
C043                  CT=0                                                     AMON  39
C044                  PCT=0                                                    AMON  40
C045                  A=0                                                      AMON  41
C046                  E=0                                                      AMON  42
C047                  AL=0                                                     AMON  43
C048                  EL=0                                                     AMON  44
C049                  ALL=0                                                    AMON  45
C050                  ELL=0                                                    AMON  46
C051                  DIAMD=.0207
C052                  DLR=(T+460.)/(MULR*528.)                                 AMON  48
C053                  DSL=7.1E-05*DLR                                          AMON  49
C054                  DGR=((T+460.)/492.)**1.5                                 AMON  50
C055                  DSG=.77*DGR                                              AMON  51
C056                  GSCON=.73
C057                IF(CPI) 141,142,141
C058             141    GP=ABS(1.05*K5*LP/K6)
C059             142    IG=1
C060                    IL=1
C061                    WRITE(IO,8001)
C062             8001 FORMAT('                    LP                  GP')
C063                    WRITE(IO,801) LP,GP
C064              801 FORMAT(2F20.6)
C                 CON
C065             2030   CPF=GP                                                 AMON  53
C066                  LPF=LP
C067                  IF(K5*LP/GP*K6) 140,140,2031
C068              140   LP=(1.-K6)*GP/(2.*K5)                                  AMON  54
C069                    WRITE(IO,9000) LP
C070             9000 FORMAT (12HOLIQUID RATE   F10.1, 80H  WAS REDUCED TO MEET MINIMUM
                    . GAS/LIQUIC RATIO FOR SPECIFIED NH3 REMOVAL                )
C071             2031 GO TO (2035, 2040, 2050, 2070, 2080), TYPE                AMON  55
C                       PART  FILM  SPLASH CROSS SPEC
C PART
C072             2035 IF(LP/(RHOL*RHOLR)-26.2) 2136,150,150
C073              150    PHI=.0672*AP**.33*(1./(RHOL*RHOLR))**.551
C074                     WET =.551
C075                     GO TO 2137
C076             2136    PHI=.0292*AP**.33*(1./(RHOL*RHOLR))**.632
C077                     WET =.632
C078             2137   DS=SQRT(AP/(3.14*NUM))                                  AMON  62
C079                    GAMA=.575*DS**.55/(AP*PHI)*SCLR**.5/MULR**.55            AMON  63
C080                    BETA=3.46*(DS/(1.-EC))**.36/(AP*PHI)*SCGR**.67/(MUGR**   AMON  64
                         .36*HENR)
C081                    PHI=PHI*LP**WET                                         AMON  65
C082                    N=.55-WET                                               AMON  66
C083                    Q=1.-WET                                                AMON  67
C084                    P=-.64                                                  AMON  68
```

```
0085                ALPHA=ALPHL/1.296E06
0086                BETAP=BETAL/3600.                                   AMON  70
0087                CT=.5                                               AMON  71
0088                 PCT=1.4*AMF1
0089                A=.375/LP**.5                                       AMON  73
0090                E=.375/LP                                           AMON  74
0091                AL=-.1875/LP**1.5                                   AMON  75
0092                EL=-.375/LP**2                                      AMON  76
0093                K7=1.13*L**.5                                       AMON  77
0094                ALL=9./32./LP**2.5                                  AMON  78
0095                ELL=.75/LP**3                                       AMON  79
0096                GO TO 2060                                          AMON  80
          C FILM
0097         2040   VO=DMATX(1,1)                                       AMON  81
0098                VNH3=VO*(.88/.47)**.67
0099                DG=DMATX(2,1)                                       AMON  83
0100                DT=DMATX(9,1)                                       AMON  84
0101                DSP=DMATX(3,1)                                      AMON  85
0102                AP=24.*(DG+DT)/(DO*(DSP+DT))                        AMON  86
0103                GAMA=0                                              AMON  87
0104                N=0                                                 AMON  88
0105                C=1                                                 AMON  89
0106                P=-.8                                               AMON  90
0107                 BETA=1./(18.*.88*HENR*VNH3*AP)
0108                ALPHA=ALPHL*RHOG*RHOGR
0109                GO TO 2060                                          AMON  93
          C SPLASH
0110         2050    VO=DMATX(14,1)
0111                 VNH3=VO*1.5
0112                 HTH=DMATX(13,1)
0113                VTH=DMATX(9,1)
0114                HSREF=DMATX(15,1)
0115                 HS=DMATX(16,1)
0116              EPS=HTH/HS
0117               VS=(DMATX(1,1)-DMATX(9,1))/12.
0118              GAMA=10.*DIAMD*(3.14/DSL)**.5*VS**.75/(1.+.56*VS)
0119              BETA=58.0*RHOL*RHOLR*DIAMD*VS**.5*GSCON*(T+460.)*
                 .     SQRT(3.14*DIAMD*RHOG*RHOGR/(2.*DSG))/(HENR*.88*(1.+3.2*VS/
                 .     1.25))
0120              EC=1.-EPS*VTH/DMATX(1,1)
0121              AP=24.*(HTH+VTH)/(HS*DMATX(1,1))
0122              HSPLH=GAMA*BETA/SQRT(GP)
0123              HFILM=LP*GP**(-.5)/(18.*.88*HENR*VNH3*AP)
0124              GAMA=0.0
0125              N=0.0
0126              C=1.0
0127              P=-.8
0128              BETA=HSPLH/(HSPLH+HFILM)/(18.*.88*HENR*VNH3*AP)
```


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0129                ALPHA=.0675*ALPHL/DMATX(1,1)*HSREF/HS*12.                    AMON 150
0130                CPA=DMATX(6,1)*(1.-EC)
                C  COMMON
                2000 K12=2.98E-4*THETA*L*ALPHA/EF**2*CLR/RHOGR**2                AMON 160
0131                                                                             AMON 165
0132                B=1./(1.-K4*LP/GP)                                           AMON 170
0133                C=GAMA*LP**N+BETA*LP**C*GP**P                                AMON 175
0134                D=ALOG(K5*LP/GP+K6)                                          AMON 180
0135                RF=.9                                                        AMON 185
0136                F=(GP/LP)**RF                                                AMON 190
0137                H=GP**(S+1.)/LP                                              AMON 195
0138                J=10.**(BETAP*LP)                                            AMON 200
0139                Y=1./LP
0140              IF(CPT) 143,210,143
0141              143 BL=K4*GP/(GP-K4*LP)**2                                     AMON 210
0142                  BG=-K4*LP/(GP-K4*LP)**2                                    AMON 215
0143                  CL=N*GAMA*LP**(N-1.)+C*BETA*GP**P*LP**(C-1.)               AMON 220
0144                  CG=P*BETA*LP**C*GP**(P-1.)                                 AMON 225
0145                  DL=K5/(K5*LP+GP*K6)                                        AMON 230
0146                  DG=-K5*LP/(K5*LP*GP+K6*GP**2)                              AMON 235
0147                  FL=-RF*GP**RF/LP**(RF+1.)                                  AMON 240
0148                  FG=RF*GP**(RF-1.)/LP**RF                                   AMON 245
0149                  HL=-GP**(S+1.)/LP**2                                       AMON 250
0150                  HG=(S+1.)*GP**S/LP                                         AMON 255
0151                  JL=2.3*10.**(BETAP*LP)*BETAP                               AMON 260
0152                  KL=-1./LP**2                                               AMON 265
0153                  BLL=2.*K4**2*GP/(GP-K4*LP)**3                              AMON 270
0154                  BGG=2.*K4*LP/(GP-K4*LP)**3                                 AMON 275
0155                  CLL=GAMA*N*(N-1.)*LP**(N-2.)+C*(C-1.)*BETA*GP**P*LP**(C-2.)AMON 280
0156                  CGG=P*(P-1.)*BETA*LP**C*GP**(P-2.)                         AMON 285
0157                  DLL=-K5**2/(K5*LP+K6*GP)**2                                AMON 290
0158                  DGG=K5*LP*(K5*LP+2.*K5*GP)/(K5*LP*GP+K6*GP**2)**2          AMON 295
0159                  FLL=RF*(RF+1.)*GP**RF/LP**(RF+2.)                          AMON 300
0160                  FGG=RF*(RF-1.)*GP**(RF-2.)/LP**RF                          AMON 305
0161                  HLL=2.*GP**(S+1.)/LP**3                                    AMON 310
0162                  HGG=S*(S+1.)*GP**(S-1.)/LP                                 AMON 315
0163                  JLL=5.3*BETAP**2*10.**(BETAP*LP)                           AMON 320
0164                  KLL=2./LP**3                                               AMON 325
0165                  ALBCD=AL*B*C*D+A*BL*C*D+A*B*CL*D+A*B*C*DL                  AMON 330
0166                  HLJ=HL*J*B*C*D+H*JL*B*C*D+H*J*BL*C*D+H*J*B*CL*D+H*J*B*C*DL AMON 335
0167                  BLCD=BL*C*D+B*CL*D+B*C*DL                                  AMON 340
0168                  KLBC=KL*B*C*D+K*BLCD                                       AMON 345
0169                  ABGC=A*BG*C*D+A*B*C*DG+A*B*CG*D                            AMON 350
0170                  HGJB=HG*J*B*C*D+H*J*BG*C*D+H*J*B*CG*D+H*J*B*C*DG           AMON 355
0171                  BGCD=BG*C*D+B*CG*D+B*C*DG
0172                  ALLB=ALL*B*C*D+2.*AL*BL*C*D+2.*AL*B*CL*D+2.*AL*B*C*DL+A*HLL*C*DAMON 360
                        +2.*A*BL*CL*D+2.*A*BL*C*DL+A*B*CLL*D+2.*A*B*CL*DL+A*B*C*CLL
                    .
0173                  HLLJ=HLL*J*B*C*D+2.*HL*JL*B*C*D+2.*HL*J*BL*C*D+2.*HL*J*    AMON 365
                    .   B*CL*D+2.*HL*J*B*C*DL+H*JLL*B*C*D+2.*H*JL*BL*C*D+2.*H*JL*B*CL*
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                .    D+2.*H*JL*B*C*DL+H*J*BLL*C*D+2.*H*J*BL*CL*D+2.*H*J*BL*C*LL+H*
                .    J*B*CLL*D+2.*H*J*B*CL*DL+H*J*B*C*DLL
0174                 HLLC=BLL*C*D+BL*CL*D+BL*C*DL+JL*CL*D+B*CLL*D+B*CL*DL+BL*C*DL+G*AMON 370
                .    CL*DL+B*C*DLL
0175                 MLLB=MLL*B*C*D+2.*ML*BL*C*D+ML*B*CL*D+2.*ML*B*C*DL+M*          AMON 375
                .    BLL*C*D+2.*M*BL*CL*D+2.*M*BL*C*DL+ML*B*CL*D+M*B*CLL*D+2.*M*B*
                .    CL*DL+M*B*C*DLL
0176                 ABGG=A*BGG*C*D+A*BG*CG*D+A*BG*C*DG+A*BC*CG*D+A*B*CGG*D+A*B*CG* AMON 380
                .    DG+A*BG*C*DG+A*B*CG*DG+A*B*C*DGG
0177                 HGGJ=HGG*J*B*C*D+HG*J*BG*C*D+HG*J*B*CG*D+HG*J*B*C*             AMON 385
                .    DG+HG*J*BG*C*D+H*J*BGG*C*D+H*J*B*CG*D+HG*J*B*C*DG+H*J*BG*CG*
                .    D+H*J*BG*CG*D+H*J*B*CGG*D+H*J*B*CG*DG+HG*J*B*C*DG+H*J*BG*C*
                .    DG+H*J*B*CG*DG+H*J*B*C*DGG
0178                 BGGC=BGG*C*D+BG*CG*D+BG*C*DG+HG*CG*D+B*CGG*D+B*CG*DG+BG*C*DG+B*AMON 390
                .    CG*DG+B*C*DGG
0179                 U=170.*K7*CT*PCT*ALBCD+136.*K7*K7*CT*PCT*ELL+PCF*K10*          AMON 395
                .    FL+CE*K12*HLLJ+CE*K11*BLCD+PCP*CPA*L*MLBC+K13*PCS*ML
0180                 V=170.*K7*CT*PCT*ABGC+PCF*K10*FG+CE*K12*HGJB+CE*K11*           AMON 400
                .    BGCD+PCP*CPA*L*M*BGCD
0181                 UL=170.*K7*CT*PCT*ALLB+136.*K7*K7*CT*PCT*ELL+PCF*K10*          AMON 405
                .    FLL+CE*K12*HLLJ+CE*K11*BLLC+PCP*CPA*L*MLLB+K13*PCS*ML
0182                 VG=170.*K7*CT*PCT*ABGG+PCF*K10*FGG+CE*K12*HGGJ+CE*K11*         AMON 410
                .    BGGC+PCP*CPA*L*M*BGGC
0183                 AC=170.*K7*CT*PCT*A*B*C*D+136.*K7*K7*CT*PCT*E+PCF*K10*         AMON 415
                .    F+PCP*K9+CE*K12*H*J*B*C*D+CF*K11*B*C*D+PCP*CPA*L*M*B*C*D
                .    +K13*PCS*M
0184                 DELTG=-V/G
0185                 WTG=GP/(GP+ABS(DELTG))
0186                 GP=GP+WTG*DELTG
0187                  IG=IG+1
0188               IF(ABS(GPF-GP)/GPF-.01) 160,160,155
0189           155 IF(IG-5) 2030,160,160
0190           160    IG=1
0191                 DELTL=-L/LL
0192                 WTL=LP/(LP+ABS(DELTL))
0193                 LP=LP+WTL*DELTL
0194                  IL=IL+1
0195               IF(IL-30) 170,200,200
0196           170 IF(ABS(GPF-GP)/GPF-.01) 180,180,2030
0197           180 IF(ABS(LPF-LP)/LPF-.01) 210,210,2030
0198           200 WRITE(IO,8005)
0199          8005 FORMAT(120HO AMMONIA OPTIMIZATION NOT CONVERGED.  TRY AGAIN WITH
                .   NEW VALUE OF LP                                                )
0200           210 Z=B*C*D
0201               TREF=(TE+TWB)/2.
0202               HCL=GAMA*LP**N+BETA*LP**Q*GP**P
0203               KA=24.6*LP/(18.*.88*HENR*HCL)
0204               TYB=EXP(1.77+.025*TWB)
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0205                GAM=KA/LP*(EXP(.025*TREF)*(5.87-.147*TREF)-IYB)
0206                BET=KA/LP*(-.147*EXP(.025*TREF)+LP/GP)
0207                TB=(GAM/BET*(1.-EXP(BET*Z))+TE*EXP(BET*Z))/(1.+KA/(BET*GP)*
                   1(EXP(BET*Z)-1.))
0208                ALP=GAM*KA/GP*TB
0209                TM=ALP/BET+(TE-ALP/BET)*EXP(BET*/)*(1.-EXP(-BET*Z))/(BET*Z)
0210                JT=JT+1
0211                CHECK=ABS(T-TM)
0212                IF(CHECK-5.) 192,192,190
0213           190  IF (JT-4) 191,192,192
0214           191  T=TM
0215           192  IF(T-TM) 194,11,194                                          AMON 470
0216           194     AC=170.*K7*CT*PCT*A*B*C*D+136.*K7*K7*CT*PCT*E+PCF*K10*
                      .  F+PCPU*K9+CE*K12*H*J*B*C*D+PCP*CPA*L*M*B*C*D
                      .  +K13*PCS*M                                            AMON 475
                       SHELL=(170.*K7*CT*PCT*A*B*C*D+136.*K7*K7*CT*PCT*E)/AMF1 AMON 480
0217                      FAN=PCF*K10*F/AMF2                                    AMON 485
0218                      PUMP=PCPU*K9/AMF2
0219                      FANPW=CE*K12*H*J*B*C*D
0220                      PUMPW=CE*K11*B*C*D                                    AMON 500
0221                      PACK=PCP*CPA*L*M*B*C*D/AMF1
0222                       STRLC=(K13-4.64*L/AMF2)*PCS*M/AMF2
0223                       CONTINUE
0224           2070    CAP=SHELL+FAN+PUMP+PACK+STRLC
0225                   XLM=4.64*L/LP
0226                   CPPG=(FANPW+PUMPW+XLM)*8337CO./(L*THETA)
0227                   DETPG=(AMF1*SHELL+AMF2*FAN+AMF2*PUMP+AMF1*PACK+AMF2*STRLC)*
0228                  1 8337CO./(L*THETA)
                       ACPG=AC*8337CO./(L*THETA)
0229                   CP=FANPW+PUMPW+XLM
0230           2080    RETURN
0231                   END
0232
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AMMONIA STRIPPING FOR WASTE WATER TREATMENT-COUNTERCURRENT TOWER

CAPITAL COSTS($)

PACKING COST	COST OF FAN	COST OF PUMP	STRUCTURE COST	TOTAL CAPITAL COST
220476.94	127205.75	20019.99	123250.62	490953.25

OPERATING COSTS($/YR.)

PUMPING POWER COST	FAN POWER COST	CHEM,LABOR,+MAIN COST	TOTAL OPERATING COST
2909.49	24300.20	24584.67	51794.36

COSTS IN CENTS PER 1000 GAL.

OPERATING COST	DEBT SERVICE	TOTAL COST
1.48	1.25	2.73

DIMENSIONS OF TOWER AND OPERATING CONDITIONS

TYPE	MEAN TEMP(F)	ENTERING CONC(MG/L)	EXIT CONC(MG/L)	
2.00	65.00	40.00	1.00	
THRUPUT(MILLION GAL/DAY)	TF(F)	TW3(F)	TW8(F)	TB(F)
13.00	70.00	65.00	95.00	64.06
LP (LB/SQ FT HR)	GP (LB/SQ FT HR)			
654.91	2837.96			
HEIGHT(FT)	AREA(SQ FT)	PRESSURE DROP (IN. WATER)		
16.47	5298.42	0.47		
REQUIRED PH	GRID HT(IN)	SPACING(IN)	THICKNESS(IN)	
10.84	4.00	1.75	0.25	

OTHER INFORMATION

AMF1	AMF2	EF	EP	CE(C/KWH)
0.800E-01	0.960E-01	0.300E 00	0.500E 00	0.800E-02
CPS(F/CU FT)	TIME(HR)	VO	ALPHA	
0.250E 01	0.840E 04	0.219E-02	0.173E-07	

```
FORTRAN IV G LEVEL 1, MOD 3          MAIN          DATE = 69206          11/54/01          PAGE 0001

0001                 REAL LP,L,KGA,KA,IE,IOS,IEC,LENTH,LM,KWKB,MAXPH
0002                 IN=5
0003                 IO=6
0004                 READ(IN,2) NCASE
0005               2 FORMAT(I3)
0006                 DO 1001 NAN=1,NCASE
0007                 READ(IN,1) CEX,CO,LP,GP,XE,TE,VO,TWB,Q,AMF1,AMF2,ALPHA,HTH,VTH,SH,
                    1VSREF,VS,EF,EP,PCTIM,CE,CPS
0008               1 FORMAT(8F10.4/,3F10.4,E10.2,4F10.4,/8F10.4)
0009                 L=3.47EC5*Q
0010                 AP=24.*(HTH*VTH)/(SH*VS)
0011                 KGA=1.5*VO*GP**.8*AP
0012                 THETA=8760.*PCTIM
0013                 KA=24.6*KGA
0014                 CP=CPS*HTH*VTH/(SH*VS)
0015                 HH=.1*EXP(.0284*TWB)
0016                 Z=29.*LP*XE*ALOG(CO/CEX)/((18.*HH*GP)*(1.-EXP(-29.*KGA*XE/GP)))
0017                 TOUT=TWB
0018                 LENTH=L/(2.*XE*LP)
0019                 VOL=2.*XE*Z*LENTH
0020                 G=2.*GP*LENTH*Z
0021                 RATIO=G/L
0022                 FAN=.0548*1.5*G**.9
0023                 PUMP=1.4*1.71*L**.6
0024                 PACK=CP*VOL
0025                 STRUT=2.*23.25*LENTH*XE
0026                 CAP=FAN+PUMP+PACK+STRUT
0027                 DETPG=(AMF2*FAN+AMF2*PUMP+AMF1*PACK+AMF2*STRUT)*833700./(L*THETA)
0028                 RHOG=.080*492./(TWB+460.)
0029                 DELTP=.0675*ALPHA*GP**2*VSREF/(SH*VS/12.*RHOG)*XE
0030                 FANPW=1.95E-06*CE*THETA*G*DELTP/(EF*RHOG)
0031                 PUMPW=3.75E-07*L/EP*THETA*CE*Z
0032                 LM=4.64*L/LP
0033                 OPER=FANPW+PUMPW+LM
0034                 OPPG=OPER*833700./(L*THETA)
0035                 ACPG=DETPG+OPPG
0036                 FRACT=(CO-CEX)/CO
0037                 KWKB=5.56E-10*EXP(-388.9/(.5555*TWB+255.2)+1.3)
0038                 HCON=(1.-FRACT)/FRACT*KWKB
0039                 MAXPH=ALOG(1./HCON)/2.3
0040                 WRITE(IO,1005)
0041          1005 FORMAT(1H0,'AMMONIA STRIPPING FOR WASTE WATER TREATMENT-CROSSFLOW
                    .TOWER')
0042                 WRITE(IO,8000)
0043          8000 FORMAT(1H1,'CAPITAL COSTS($)'    )
0044                 WRITE(IO,8003)
0045          8003 FORMAT(120HO           PACKING COST      COST OF FAN          COST O
                    .F PUMP       STRUCTURE COST      TOTAL CAPITAL COST                )
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0046                WRITE(IO,801) PACK,FAN,PUMP,STRUT,CAP
0047          801       FORMAT(5F20.2)
0048                WRITE(IO,8002)
0049         8002 FORMAT(1HO,'OPERATING COSTS($/YR.)'  )
0050                WRITE(IO,8004)
0051         8004 FORMAT(120HO      PUMPING POWER COST  FAN POWER COST  CHEM,LABOR,+
                    .MAIN COST    TOTAL OPERATING COST                              )
0052                WRITE(IO,801) PUMPW, FANPW,LM,OPER
0053                WRITE(IO,700)
0054          700 FORMAT(1HO,'COSTS IN CENTS PER 1000 GAL.'  )
0055         8005 FORMAT(120HO            OPERATING COST      DEBT SERVICE        TOT
                    .AL COST                                                       )
0056                WRITE(IO,8005)
0057                WRITE(IO,801) OPPG,DETPG,ACPG
0058                WRITE(IO,9000)
0059         9000 FORMAT(1HO,'DIMENSIONS OF TOWER AND OPERATING CONDITIONS'  )
0060          901       FORMAT(6F20.2)
0061                WRITE(IO,9001)
0062         9001 FORMAT(1HO,'                WIDTH(FT)     GAS-LIQUID RATIO        a,
                    L'ENTERING CONC(MG/L)   EXIT CONC(MG/L)                        a)
0063                WRITE(IO,901) XE,RATIO,CO,CEX
0064                WRITE(IO,9003)
0065         9003 FORMAT(1HO,'     THRUPUT(MILLION GAL/DAY)       TF(F)            ',
                    .' Tw8(F)          EXIT TEMP(F)      ')
0066                WRITE(IO,901) Q,TE,TWB,TOUT
0067                WRITE(IO,9004)
0068         9004 FORMAT(50HO        LP (LB/SQ FT HR)    GP (LB/SQ FT HR)          )
0069                WRITE(IO,901) LP, GP
0070                WRITE(IO,9005)
0071         9005 FORMAT(120HO              HEIGHT(FT)       LENGTH(FT)     PRESSURE
                    .DROP (IN. WATER)                                              )
0072                WRITE(IO,901) Z,LENTH,DELTP
0073                WRITE(IO,9006)
0074         9006 FORMAT(120HO          REQUIRED PH              HTH(IN)
                    .VTH(IN)              SH(IN)              VS(IN)               )
0075                WRITE(IO,901) MAXPH,HTH,VTH,SH,VS
0076                WRITE(IO,9007)
0077         9007 FORMAT(1HO,'OTHER INFORMATION')
0078                WRITE(IO,9008)
0079         9008 FORMAT(120HO                AMF1                AMF2
                    .FF                  EP                CE(C/KWH)            )
0080                WRITE(IO,905) AMF1,AMF2,FF,EP,CE
0081          905 FORMAT(5E20.3)
0082                WRITE(IO,9009)
0083         9009 FORMAT(120HO      CPS($/SOLID CU FT)          PC TIME
                    .  VO                ALPHA               VSREF(IN)            )
0084                WRITE(IO,905) CPS,PCTIM,VO,ALPHA,VSREF
0085         1001 CONTINUE
```

CAPITAL COSTS($)

PACKING COST	COST OF FAN	COST OF PUMP	STRUCTURE COST	TOTAL CAPITAL COST
178777.34	547150.62	20105.78	134462.37	880496.69

OPERATING COSTS($/YR.)

PUMPING POWER COST	FAN POWER COST	CHEM.,LABOR,+MAIN COST	TOTAL OPERATING COST
3267.36	119826.87	26834.66	149868.81

COSTS IN CENTS PER 1000 GAL.

OPERATING COST	DEBT SERVICE	TOTAL COST
4.29	2.33	6.61

DIMENSIONS OF TOWER AND OPERATING CONDITIONS

WIDTH(FT)	GAS-LIQUID RATIO	ENTERING CONC(MG/L)	EXIT CONC(MG/L)
10.00	10.99	40.00	1.00

THRUPUT(MILLION GAL/DAY)	TE(F)	TWB(F)	EXIT TEMP(F)
10.00	70.00	60.00	60.00

LP (LB/SQ FT HR)	GP (LB/SQ FT HR)
600.00	2400.00

HEIGHT(FT)	LENGTH(FT)	PRESSURE DROP (IN. WATER)
27.48	289.17	0.92

REQUIRED PH	HTH(IN)	VTH(IN)	SH(IN)	VS(IN)
10.80	1.50	0.38	2.00	1.50

OTHER INFORMATION

AMF1	AMF2	EF	EP	CE(C/KWH)
0.800E-01	0.960E-01	0.500E 00	0.750E 00	0.800E-02

CPS($/SOLID CU FT)	PC TIME	VO	ALPHA	VSREF(IN)
0.600E 01	0.960E 00	0.300E-02	0.400E-08	0.112E 01

AMMONIA STRIPPING FOR WASTE WATER TREATMENT-CROSSFLOW TOWER

NOMENCLATURE

Each entry in the following list may contain: name of identifier in computer program, mathematical symbol in report given in parentheses (if different from name of identifier), explanation of identifier, units.

A	combined function in cost eq.
ABGC	combined function in derivation of cost eq.
ABGG	combined function in derivation of cost eq.
AC	total annual cost, $/yr
ACPG	total annual cost, ¢/1000 gal
ACGAL	$ cost per 1000 gal (only in program)
AL	$\partial A/\partial LP$
ALBCD	combined function in derivative of cost eq.
ALL	$\partial^2 A/\partial LP^2$
ALLB	combined function in derivative of cost eq.
ALPHA, ALPHAL	corrected for units (only in program)
ALPHAL	parameter for pressure drop eq.
AMF1	amortization factor (only in program)
AMF2	amortization factor (only in program)
AP (a')	surface area of packing per unit volume of packing, ft^2/ft^3
AREA	cross-sectional area of towers, ft^2
B	combined function in cost eq.
BETA (B)	parameter for height of a transfer unit eq.
BETAL (B')	parameter for pressure drop eq.
BETAP, BETAL	corrected for units (only in program)

BG	$\partial B/\partial GP$
BGG	$\partial^2 B/\partial GP^2$
BGCD	combined function in derivative of cost eq.
BGGC	combined function in derivative of cost eq.
BL	$\partial B/\partial LP$
BLCD	combined function in derivative of cost eq.
BLL	$\partial^2 B/\partial LP^2$
BLLC	combined function in derivative of cost eq.
CAP	total capital cost
C	combined function in cost eq.
C_B	cost of structure, $/ft^2
CE	cost of electricity, $/KWH
C_G	concentration of gas
CG	$\partial C/\partial GP$
C_{OG}	entering concentration of gas
CGG	$\partial^2 C/\partial GP^2$
C_L	concentration of liquid
CL	$\partial C/\partial LP$
C_{LM}	cost of labor and maintenance, $/ft^2
CLL	$\partial^2 C/\partial LP^2$
C_{OL}	entering concentration of liquid
CONCO2	conc. of CO_2 (only in program)
CONOHT	[OH] at top of tower (only in program)
CO2R	ratio of CO_2 in air entering and leaving (only in program)
CO2TRS	amount of CO_2 transferred (only in program)
CPA (Cp)	packing cost, $/ft^3
C_{PL}	specific heat of liquid
CT	unit cost of steel shell
C*	gas concentration in equilibrium with bulk liquid concentration

D	combined function in cost eq.
DELTAP (AP)	pressure drop, in. H_2O
DELTG	increment of GP for next iteration (only in program)
DELTL	increment of LP for next iteration (only in program)
DETPG	debt service, ¢/1000 gals
DG	height of a film grid
DGG	$\partial^2 D/\partial GP^2$
DGR	temperature correction factor for gas diffusivity p. 22
DIAM	diameter of tower, ft
DL	$\partial D/\partial LP$
DLL	$\partial^2 D/\partial LP^2$
DLR	temperature correction factor for liquid diffusivity
DS	equivalent diameter of a particle packing (only in program)
DSG	gas diffusivity
DSL	liquid diffusivity
DSP	spacing of film grids
DT	thickness of a film grid
E	combined function in cost equation
EF	efficiency of fan
EL	$\partial E/\partial LP$
ELL	$\partial^2 E/\partial LP^2$
EO	porosity
EP	efficiency of pump
EPS	planar solidity of splash packing
F	combined function in cost equation,
FAN	installed cost of fan (only in program)
FANPOW	annual cost of fan power (only in program)

FG	$\partial F/\partial GP$
FGG	$\partial^2 F/\partial GP^2$
FL	$\partial F/\partial LP$
FLL	$\partial^2 F/\partial LP^2$
FRACT	fraction of free NH_3
G	gravitational constant 32.2 ft/sec^2
GAMA (8)	parameter for height of a transfer unit eq.
GASCON	universal gas constant
GF (G_F)	gas flooding rate, lb/hr ft^2
G	gas rate lb mole/hr ft^2
GP (G)	gas rate, lb/hr ft^2
GPF	previous value of GP in iterative scheme (only in program)
H	combined function in cost eq.
HCONC	$[H^+]$ conc.
HENCO2	Henry's Constant for CO_2-H_2O (only in program)
HENR	temperature correction factor for Henry's Constant for NH_3-air-H_2O system
HG	$\partial H/\partial GP$
HGG	$\partial^2 H/\partial GP^2$
HGGJ	combined function in derivative of cost eq.
HGJB	combined function in derivative of cost eq.
HL	$\partial H/\partial LP$
HLJ	combined function in derivative of cost eq.
HLL	$\partial^2 H/\partial LP^2$
HLLJ	combined function in derivative of cost eq.
HS	horizontal spacing of splash bars
HTH	horizontal thickness of a splash bar
i	enthalpy of air, Btu/lb

i*	enthalpy of air in equilibrium with bulk liquid temperature
i_e	entering enthalpy of air
J	combined function for annual cost eq.
JL	$\partial J/\partial L$
JLL	$\partial^2 J/\partial L^2$
K4	combined constant in eq. for no. of transfer units (only in program)
K5	combined constant in eq. for No. of transfer units (only in program)
K6	combined constant in eq. for No. of transfer units (only in program)
K7	combined constant for steel shell for particle packing
K9	combined constant for pump cost (only in program)
K10	combined constant for fan cost
K11	combined constant for pumping cost
K12	combined constant for fan power
K13	combined constant for basin cost (only in program)
Ka	enthalpy transfer coefficient
KB	equilibrium constant for NH_3-H_2O
KGA	gas phase mass transfer coefficient for CO_2 absorption (only in program)
K_Ga	overall gas phase mass transfer coefficient
KLA (K_La)	overall liquid phase mass transfer coefficient for CO_2 absorption
KWKB	ratio of ion product for H_2O and equilibrium constant for NH_3-H_2O
L(L_T)	liquid thru put, lb/hr,
L	liquid rate lb mole/hr ft^2
LM	annual chemical, maintenance and labor cost

LP(L)	liquid rate, lb/hr ft^2
LPF	previous value of LP in iterative scheme (only in program)
M	dimensionless Henry's constant
M	combined function for annual cost eq.
MINPH($pH_{maximum}$)	minimum pH
ML	$\partial M/\partial LP$
MLL	$\partial^2 M/\partial LP^2$
MLBC	combined function in the derivative of the annual cost (only in program)
MLLB	combined function in the derivative of the annual cost (only in program)
MPHDRP	maximum pH drop (only in program but see p.7 and 20)
MUGR	temperature correction factor for gas viscosity
MULR	temperature correction factor for liquid viscosity
MUW(μ_w)	viscosity of water
N(n)	parameter for height of a transfer unit eq.
NH3OUT	required exit conc. of NH_3, mg/l
NUM	for particle packing only, No. of packings per unit volume of packing
OHDRPA	[OH] drop due to NH_3 change
OP	total annual operating cost $
OPPG	total annual operating cost, ¢/1000 gal
P (p)	parameter for height of a transfer unit eq.
PACK	installed cost of packing (only in program)
PCF	% of capital cost of fan for purchase, installation and amortization
PCP	% of capital cost of packing for purchase, installation and amortization

PCPU	% of capital cost of pump for purchase, installation and amortization
PCS	% of capital cost of structure for purchase, installation and amortization
PHI (Ø)	fraction of packing actually wetted.
PUMP	installed cost of pump (only in program)
PUMPW	annual cost of pump power (only in program)
Q (q)	parameter for height of a transfer unit eq.
RF	parameter for fan cost eq. (only in program)
RHOG	gas density at 68°F, .0753 lb/ft^3
RHOGR	temperature correction factor for gas density
RHOL	density of H_2O at 68°F, 62.3 lb/ft^3
RHOLR	temperature correction factor for liquid density
S	parameter for pressure drop eq.
SCGR	temperature correction factor for Schmidt of gases,
SCLR	temperature correction factor for Schmidt No. for liquids,
SHELL	installed cost of steel shell (only in program)
STRUCT	installed cost of structure, etc. (only in program)
T	design temperature, °F (only in program)
TDB	dry bulb temperature, °F
THETA	time of operation hrs/yr
t_L	temperature of liquid
t_{Le}	entering temperature of liquid

VO (v_o)	parameter for correlation of mass transfer coefficient for film packing
VS	vertical spacing of splash bars
VTH	vertical thickness of splash bars (only in program)
WET	parameter in wetted area eq.
WTG	weighting factor for new trial value of GP (only in program)
WTL	weighting factor for new trial value of LP (only in program)
X	width of tower, ft
Y	length of tower, ft
Z	height of tower, ft

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